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BASIC STUDY OF AIR POLLUTION CONTROL WET SCRUBBERS

BY

SEYMOUR CALVERT

Chemical Engineering Division

CASE INSTITUTE OF TECHNOLOGY
CLEVELAND, OHIO

U. S. Public Health Service Research Grant S-84

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16. Abstracts The specific aims of the research are to define the interrelationships among heat and mass transfer and the collection of particulates and fluid properties, flow rates, system geometry, particle properties, etc. for the following systems: (1) contact with liquid drops under circumstances which promote circulation within the drops; (2) contact with liquid in the form of froth; and (3) contact with wetted surfaces in geometries which provide strong secondary flow patterns in the gas. It was found that both transport rates and particulate collection might be increased considerably by employing a scrubber especially designed to promote the mechanism of drop oscillation. All of the research is based on thesis investigations on: (1) liquid drops with internal circulation; (2) baffled conduits; (3) froth systems; and (4) automatic control. Details of these several investigations are given with charts and references included.

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Interim Progress Report on

BASIC STUDY OF AIR POLLUTION CONTROL

WET SCRUBBERS

U.S. Public Health Service Research Grant S-84

by

Professor Seymour Calvert
Principal Investigator

and

Gus Constan
George Coulman
Fay Fun
Yhuda Goldshmid
Ralph Hodous
Thomas Sweeney
Eugene Weissman
Walter Workman

January 13, 1961

Chemical Engineering Division
Case Institute of Technology

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INTRODUCTION

This progress report is written in order to enable the review of the work which has been and is being carried out under U.S.P.H.S. Research Grant S-84. Detailed reporting of this work will be in the forms of journal publications and completed thesis reports. At present one journal reprint is available, two papers have been submitted for publication, one M.S. thesis is completed, one Ph.D. thesis is being typed, and six Ph.D. theses are at various stages of completion. Because of the large quantity of material which will be reported in final form during the coming year or so this report will cover only the highlights of the work.

A brief summary of the nature of the research under this grant is provided by the original research proposal. A portion of that proposal is quoted here:

"Research Plan

The proposed research would be an academic research program (i.e., including doctoral and masters thesis work) on certain fundamental aspects of gas scrubbing equipment; in particular of low pressure drop equipment such as is commonly applied to air pollution control. The specific subject matter of the program would be the investigation of several gas-liquid contacting mechanisms which show evidence of being especially effective.

A. Specific Aims

The specific aims of the research would be to define as completely as possible the inter relationships among heat and mass transfer and the collection of particulates and fluid properties, flow rates, system geometry, particle properties, etc., for the following systems:

1. Contact with liquid drops under circumstances which promote circulation within the drops.

2. Contact with liquid in the form of froth.

3. Contact with wetted surfaces in geometries which provide strong secondary flow patterns in the gas.

B. Method of Procedure

The primary method of procedure would be to define and carry out specific studies as doctoral thesis programs with exploratory and ancillary studies to be carried out as masters thesis programs. These programs would be coordinated by the principal investigator and would be augmented by his work plus that of part-time student research assistants.

The first system to be studied would be contacting with liquid drops. Since it is conceivable that a thorough investigation of this problem alone could occupy the entire time period proposed,

it would be impossible to predict the extent to which the remaining two systems could be investigated. The plan would be to "phase them in" as the progress on the first problem warranted.

The proposed approaches to the specific aims are as follows:

1. The effect of circulation within drops would be studied by means of two principle techniques:

   a. Drops suspended on hypodermic tubing with controlled liquid circulation through the drop.

   b. Drops suspended on surfaces such as wires with circulation provided through oscillation, entrainment, and re-deposition.

   In both cases the first studies would be of single drops. The second case (b.) would also include a study of populations of drops.

2. Contacting in froth systems would be studied in small packed and unpacked conduits which will provide co-current, countercurrent, and mixed (or stagewise)contacting of liquid and vapor.

3. The effect of secondary flow patterns on transport rates would be determined for each of the principle types of secondary flow. One type is the radial flow induced by the axial flow of a fluid through a conduit of non-circular cross section. Another type is that caused by flow around a conduit bend. Still another is that caused by eddy formation behind solid obstacles.

General Conditions

The particular systems of fluids and contaminants (or transferring components) to be employed in the above studies will be very similar and in many cases the same for all of the studies. The major vapor constituent will be air and in most cases the major liquid constituent will be water. Other liquids will be employed when required for variation of fluid properties and for provision of special characteristics such as low vapor pressure when heat transfer without simultaneous mass transfer is being investigated.

Particulate contaminants will be provided by means of dust dispersion, condensation on nuclei, atomization, atomization followed by drying, and the formation of metal oxide fumes. Vapor contaminants will include water, sulfur dioxide, carbon dioxide, ketones, alchols, and others.

The scale of the apparatus will be quite small for the studies of drops and slightly larger for studies of secondary flow and froth systems. Thus the vapor rate would range from about 1 CFM to about 500 CFM.

The apparatus would generally be transparent in order to enable observation and motion picture photography.

C. Significance of this Research

The proposed research would be significant to the field of public health and particularly to air pollution control engineering in that:

1. The particular gas-liquid contacting mechanisms to be investigated show promise of being especially effective. Having a quantitative definition of these transport phenomena would enable us to:

   a. Decide whether it would be worthwhile to design gas scrubbing equipment in which the existence of these mechanisms is encouraged and, if desirable, to design for optimum effectiveness.

   b. Evaluate the effects of these mechanisms (e.g. circulation within drops) in presently employed scrubber designs.

2. The research will be important to both our general educational program in air pollution control engineering and to the encouragement and support of advanced study and thesis research in this area.

As a specific example of the first point presented we might consider the case of circulation within drops. Results obtained by others (see below) indicate that circulation within drops and the distortion of drops can have a great effect on overall mass and heat transfer rates in cases where liquid phase resistance is controlling. Further, it has been observed by this investigator and others that the collection of particulates is much more efficient in wetted fibrous filters (impingement type) than in dry fibrous filters. It seems quite probable that the difference in collection efficiency is due to the high efficiency of collection by liquid drops on the fibers (rather than the provision of a "tacky" film on the fibers).

Finally, it has been observed by this investigator by means of high speed movies that liquid drops suspended on wires and under the influence of a gas stream are far from tranquil as the gas velocity approaches the "flooding" velocity. There is extreme oscillation and deformation of the drop with the result that the drop surface is stretched to several times that of a sphere with the same volume.

Putting these pieces of evidence together we come to the conclusion that both transport rates and particulate collection might be increased considerably by employing a scrubber especially designed to promote this mechanism of drop oscillation.

Approach Taken

Since the time of initiation of this grant (September 1, 1958) the work has remained pretty much within the scope of the original proposal. The major departure has been from the anticipated timing, which foresaw a necessity for sequential applications of effort on the several systems proposed for study. As it happened, however, several students who had other financial support were attracted to this work and it became possible to extend the research effort beyond the anticipated level without increasing the budget. Through these fortuitous circumstances it was also necessary to initiate work on all three of the proposed systems plus an additional study of optimal automatic control of a gas scrubbing system.

All of the research is based on thesis investigations so that each problem is studied by an individual graduate student under the supervision of the principal investigator. Consequently, each of the several problems is identified with the name of the student who carried out the work. There has been group effort where the use of common facilities, analytical devices, techniques, etc., were advantageous. From time-to-time it has also been advantageous to hire non-thesis personnel for supporting tasks such as particle counting, equipment calibration, photographic work, etc.

SUMMARY

Brief summaries for each of the problems are given in this section. More detailed reports for most of these are given in a later section. The subjects are identified by thesis titles and students names.

LIQUID DROPS WITH INTERNAL CIRCULATION

1. Mass Transfer in Drops under Circumstances which Promote Oscillation and Internal Circulation, Gus Constan (Ph.D. Thesis)--Experimental and analytical work is completed for this study. Mr. Constan is presently having his thesis typed and is scheduled to have his oral (final) examination at the end of January, 1961. Copies of the thesis will be submitted to the U.S.P.H.S. following approval. A paper based on the thesis will be submitted to the American Institute of Chemical Engineers for publication.

Abstract

Single drops supported on hypodermic tubing have been studied in a wind tunnel to determine the effect of drop oscillation on mass transfer. The system studied for the case where internal resistance controls consisted of absorption of SO_2 gas by drops of glycerine, propylene glycol, and ethylene glycol. The results can be expressed in terms of effective diffusivity.

No significant effect on internal coefficient was noted in glycerine, whereas the glycols gave effective diffusivity values of 2 - 8 times the molecular diffusivity.

Frequencies, amplitudes, and internal circulation velocities in the drops were studied by cinematography, and are in agreement with predicted magnitudes.

The effect of oscillation on external mass transfer coefficients was studied by sublimation of naphthalene spheres. In the cases where the vibrational velocity was less than the stream velocity, no effect was noted; this is in agreement with heat transfer studies.

A technique has been developed for studying the effect of internal circulation of effective diffusivity, using forced circulation through a drop suspended on hypodermic tubing. A "pseudo-film thickness" is determined as a function of circulation velocity, and presents a means of predicting effective diffusivity. This technique has been demonstrated for the system SO_2-H_2O, giving results in fair agreement with the correlation of Garner and Lane[17] of N_{Re} versus effective diffusivity.

The significance of this knowledge to gas scrubber design is that rates of gas absorption by liquid drops oscillating about a solid support may be estimated. If the absorption process is gas-phase controlled (very soluble gas) there is no benefit obtained from the oscillation. If the absorption is liquid-phase controlled (slightly soluble gas) the oscillation is beneficial. It becomes necessary to determine the influence of other factors (see Fay Fun thesis below) in order to incorporate the knowledge of single oscillating drops into the design of a complete scrubber.

2. Particulate Collection by Single, Oscillating, Supported Drops, Yhuda Goldshmid (Ph.D. Thesis). Experimental work is about 2/3 completed and analytical work about 1/2 completed for this study. Mr. Goldshmid will probably complete his thesis by September, 1961.

Abstract

Collection efficiencies have been determined for polystyrene particles being captured by single drops of several liquids supported on hypodermic needle tubing. The effect of surface forces between the liquid and the particles proves to be of primary importance. The effect of oscillation in the range of air velocities up to the point of drop disengagement appears to be of marginal importance. Appreciable collection efficiencies are attained for values of the inertial collection parameter, $N_D = \left(\frac{\rho_p \mu_o}{9 \eta_g D_c}\right) 1/2 D_p$, much lower than 0.2, below which many investigators have reported and predicted theoretically that the impaction efficiency should be zero. The liquids used were water, glycerol, m-methoxyphenol, and formamid.

The aerosol used was prepared by spray-drying polystyrene latex prepared by The Dow Chemical Company. The particle sizes were 0.814, 1.171, 1.8, and 2.85 micron diameter. Aging of the surface active agent present in the latex proved to have a significant effect

on the collection efficiency for the tyo smaller sizes. Because of this and additional doubt as to particle size distribution the data on polystyrene collection may not be considered entirely reliable until they can be compared with data for purer monodispersed aerosols.

Data are presently being taken on stearic acid aerosols prepared by the La Mer method. Liquids providing a significant range of physical properties will be used for collection drops. Similar data will then be taken on ammonium chloride aerosol. Theoretical analysis based on a mathematical model which includes surface, drag, and Van der Waals forces is in progress.

3. Particulate Collection and Gas Absorption in Packed Columns which Promote Liquid Oscillation and Circulation, Fay Fun (Ph.D. Thesis). Experimental apparatus construction is nearly completed. Mr. Fun will probably complete this study next fall or early in 1962.

Abstract

The work of Constan and Goldshmid on single oscillating drops provides a fairly comprehensive picture of one of the phenomena involved in gas scrubbers. In order to incorporate this information into the analysis or design of a scrubber it is necessary to define the other allied phenomena which make up the total physical system. The use of hypodermic needle tubing to convey the liquid to the drop provides a useful experimental technique from the point of view of enabling the use of controlled volume, stable oscillating drops. From the point of view of analysis of an entire scrubbing system, however, it limits the range of study.

Where a large population of drops must be provided it is most likely that the scrubbing system will be composed of a bed packed with slender elements, means for introducing liquid at one or perhaps a few planes in the bed, and means for removing liquid from the bed. Oscillation and circulation may be provided by operation near the flooding point region, by mechanically shaking the bed, or by introducing pulsations in the gas flow rate. The first of these three modes of operation has been chosen for this study.

The phenomena which will be involved in near-flooded bed operation are collection of liquid drops on packing elements, oscillation of drops on elements, coalescence of drops, detachment and shatter of drops, and (for counter-current operation) run down of drops and streams. The experimental apparatus has been designed to provide means for studying all of these interacting phenomena. The basic component of the apparatus is a 4-inch I.D. glass column which can be fitted with various packing arrays and which can be operated in either co-current or counter-current fashion. Both gas absorption and small particle collection will be studied.

BAFFLED CONDUITS

1. Collection of Small Particles in Baffled Conduits, Ralph Hodous (M.S. Thesis). This thesis was completed in June, 1960, and a paper has been presented at the A.I.Ch.E. Meeting in Washington, D. C., December, 1960. Publication by the A.I.Ch.E. is anticipated.

Abstract

Small particle collection in baffled conduits has been studied as one aspect of the general subject of collection in secondary flow systems. The secondary flow patterns, or eddies, form behind each of a series of baffles affixed to one wall of a rectangular cross-section conduit and alligned perpendicular to the major fluid flow direction. This study involved experimental determinations of collection efficiency and pressure drop for titanium dioxide aerosols flowing through dry baffled conduits with various baffle heights and free space above baffle combinations.

Inertial collection efficiency is well represented by a mathematical model involving one empirical constant. Pressure drop varies with the 1.7 power of air velocity and is correlated by means of an empirical equation.

The relationships developed in this research may be applied to the design of baffled conduit collection systems of the type studied. This system provides good efficiency in the 1 - 2 micron size range and a collection efficiency-power requirement relationship which compares favorably with those for presently used scrubbers.

2. Mass Transfer in Secondary Flow Systems, Thomas Sweeney (Ph.D. Thesis). Experimental work is under way and completion of Mr. Sweeney's thesis is expected by late summer or fall of 1961.

Abstract

Mass transfer in rectangular baffled conduits is the portion of the general secondary flow problem which is being studied in this research. Preliminary analysis based on penetration theory and the literature on heat transfer to extended surfaces indicates that liquid-phase coefficients should be comparable to those for packed columns and that gas-phase coefficients should be better.

Both liquid- and gas-phase controlled systems are being studied. The baffled conduit is employed as a vertical column with baffles on one or both of the wide sides. Difficulties with liquid distribution in the first apparatus designed have necessitated the modification of the columns to provide for better distribution.

This apparatus has been designed with provisions for the subsequent study of small particle collection in wetted baffled conduits. It is anticipated that the performance on mass transfer will be strongly related to collection of fume by the diffusional mechanism.

8<

FROTH SYSTEMS

1. Mass Transfer and Particulate Collection in Supported Froths, Walter Workman (Ph.D. Thesis). Preliminary experiments on small scale apparatus are substantially complete and experiments on larger apparatus are under way. Mr. Workman should complete his thesis work by about September, 1961.

Abstract

Froth systems have been defined for our purposes to mean those in which a gas is dispersed in a liquid. The relative proportions of gas and liquid held up in the froth may vary over a wide range. This study covers the general area of high liquid to gas holdup ratio while the study of Weissman (see below) covers the region of low liquid to gas holdup ratio.

The ultimate problem of interest is the behavior of large populations of bubbles as related to mass transfer and small particle collection. Preliminary work directed toward this problem has been carried out with laboratory (or analytical) size bubbling absorbers. One aspect of the small-scale work has been the analysis and development of methods for predicting gas absorption efficiency. Two papers have been written on this topic - "Estimation of Efficiency for Bubbler-Type Gas Absorbers", Calvert and Workman, Talanta, 4, 89 (1960) and "The Efficiency of Small Gas Absorbers", Calvert and Workman, submitted to Analytical Chemistry.

The other aspect of the small-scale work is the study of co-current flow effects in a spiral core (Milligan type) absorber. Co-current flow occurs to some extent in all types of bubbling (froth) absorbers and to a large extent in devices such as the spiral absorber and the larger scale egg-crate packed contactor (described below) where definite flow channels are provided. Modification of a standard spiral absorber to permit steady-state operation with a continuous flow of liquid has enabled the determination of flow and absorption rates. Analysis of the data from these experiments is not yet complete but first indications are that the results are consistent with the mathematical models which have been developed.

Investigation of large populations of bubbles is being carried out in an egg-crate packed contactor. Froth is initially generated by the passage of gas upward through a perforated plate. The froth height can be extended considerably by the insertion of egg-crate packing above the perforated plate and variations of this arrangement are being investigated. Published results by Russian investigators indicate that perforated plate froth apparatus provides good collection efficiency but their work has been restricted to large particle sizes. The present research will cover the collection of smaller particles down to the fume range as well as gas absorption.

2. Mass Transfer and Particulate Collection in Co-Current Foam Systems, Eugene Weissman (Ph.D. Thesis). Apparatus has been built and preliminary runs have indicated feasibility of

horizontal co-current foam contacting. Mr. Weissman should complete his thesis by about the end of 1961 or early 1962.

Abstract

Co-current foam systems appear to be most suitable for providing low liquid to gas holdup ratios and thereby extremely large surface area per unit of liquid volume. Because no investigations of this type of system have been reported in the literature and because of the complexities of the system, the initial experimental work is almost entirely exploratory. The ultimate objectives are to determine the flow, absorption, and particle collection behavior of co-current foam systems.

It is first necessary to devise meaningful and controllable experiments which will provide the desired system and also permit variations in flow direction and other parameters. The foams produced will be both of the individual bubble type and the condensed, polyedric type. Gas absorption studies will include both gas- and liquid-phase controlled systems. Particle collection will be studied in the sub-micron size range and will also include variations in wettability. The present apparatus has given promising performance in horizontal flow of polyedric foam.

AUTOMATIC CONTROL

Automatic Control and Dynamics of a Gas Scrubbing System, George Coulman (Ph.D. Thesis). Equipment construction and preliminary mathematical analysis are nearing completion. Mr. Coulman will conclude this study by about September, 1961.

Abstract

This research involves the mathematical description of a gas absorption column for unsteady state operation and the justification of this model by a pilot unit experimental study. The purpose of this study is to allow application of an optimizing control system to the absorption column.

It is specifically concerned with the operation of a waste gas scrubbing system which may be continually disturbed by changes in gas rate and composition such as from a smelting installation. In this case the disturbances are measurable but usually unpredictable. The disturbances are quite often of significant magnitude and transient periods an appreciable portion of the operating time. With this type of system either feed forward control system or another type of unique control system may be applicable. In any case a knowledge of the dynamics is needed to justify a more or less sophisticated control system. If the control system is justified, the dynamics are again needed for the operation of an unsteady-state optimizing control system or for the design of any simplified form of this type of control.

The experimental data would include the concentration response of the outlet streams to a step and/or impulse deviation in the inlet gas composition. This data would be collected hopefully

for forced isothermal condition and for significant thermal effects. This work would all be performed at constant carrier stream rates in order to relate to the analog simulation program for these conditions.

A final experiment for a first look at a feed forward control system would be a start-up. This would involve filling the column with liquid, maintaining an operating air stream with no liquid feed, introducing a step change in the inlet gas composition, waiting until the exhaust gas approaches the operating level and then bringing the liquid feed to the operating level. Since the liquid feed will be adjusted to a level based on the gas feed composition level, it is basically a feed-forward proportional control with a pure time delay. Modification of this experiment and similar experiments with concentration control in the liquid stream would be of interest for preliminary study of feed-forward control with a minimum of dynamics knowledge of the process.

DETAILED REPORTS

Detailed reports are presented in the following appendices. Several of these are in the form of technical papers and others in the form of interim progress reports. The research on mass transfer to single drops will be reported in the near future as Mr. Constan's Ph.D. Thesis. Copies of this thesis will be mailed to the U.S.P.H.S. on about the middle of February, 1961.

The appendices presented are as follows:

1. Appendix A--"Mass Transfer in Drops under Circumstances which Promote Oscillation and Internal Circulation," (to be mailed separately, as noted above).

2. Appendix B--Interim Progress Report on "Particulate Collection by Single, Oscillating, Supported Drops."

3. Appendix C--Interim Progress Report on "Particulate Collection and Gas Absorption in Packed Columns which Promote Liquid Oscillation and Circulation."

4. Appendix D--Technical paper on "Collection of Small Particles in Baffled Conduits."

5. Appendix E--Interim Progress Report on "Mass Transfer in Secondary Flow Systems."

6. Appendix F--Reprint of "Estimation of Efficiency for Bubbler-Type Gas Absorbers."

7. Appendix G--Technical paper on "The Efficiency of Small Gas Absorbers."

8. Appendix H--Interim Progress Report on "Mass Transfer and Particulate Collection in Supported Froths."

CONCLUSIONS

The overall research program under Grant S-84 has developed into a more extensive effort than originally anticipated and has been most gratifying as an academic research program. Some of the individual studies are now completed and have already or will soon provide significant additions to the literature. The studies which are still in progress all appear to be proceeding satisfactorily. As will be indicated below, the results obtained thus far point out directions for future work.

Single oscillating drop studies have shown that at best moderate increases in contacting efficiency may be obtained within the regime of stable oscillation about support wires. The mass transfer processes within this regime can be defined with fair accuracy for purposes of prediction. The particle collection process has not yet been completely defined and the most significant effect observed is that of surface properties. The behavior of large drop populations and the influence of the several mechanisms involved in operation in the unstable regime appears to be an interesting area of study. Additional emphasis on the effect of surface forces is indicated for this and other collection systems.

Baffled conduits have been shown to be quite effective for the collection of particles. The information obtained thus far provides a basis for the design of dry baffled collectors with geometry comparable to that studied. Experimental results on mass transfer are not yet available but predictions based on hypothesis indicate that baffled conduits should have good characteristics. Further studies of particle collection in wetted baffled conduits and the effects of baffle geometries are definitely indicated.

Froth system studies have led to useful analyses of the performance of small absorbers as part of the initial phase of the work. The use of froth supporting packing has been shown to provide a means of controlling froth height. While the only data available are from the Russian work on particle collection in high density foams, both of the studies in progress appear quite promising.

Automatic control of gas scrubbers is an area which was not part of the original proposal but one which is quite interesting, especially in view of the transition to automated operation of manufacturing plants. Present indications are that the optimization factors will be more significant than dynamic factors. Experimental verification or disproof of present mathematical theory is necessary.

APPENDIX B

Interim Progress Report on

PARTICLE COLLECTION BY OSCILLATING DROPS

Yhuda Goldshmid

Introduction

The general subject of this research is a basic study of the collection of small particles by single oscillating drops. The specific problem concerns monodisperse aerosols containing particles in about the 0.5 to 3.0 micron diameter range, so that the inertial mechanism is predominant over most of the range, and drops which are suspended on relatively slender horizontal supports, such as hypodermic tubes. Oscillation of the drop is caused by an upward flowing air stream and the air velocity is varied up to the point at which the drop will be blown away from the support.

The major questions regarding this system were how to define the effect of the unsteady gas flow patterns resulting from oscillation and how to define the influence of surface forces. As a preliminary step it was necessary to explore the range of possible drop diameters and gas velocities consistent with stable operation.

The variables which are being studied are as follows:

1. Particle characteristics
   a. Diameter
   b. Composition (and consequent properties such as density and surface)
2. Collection drop characteristics
   a. Diameter
   b. Composition
3. Supporting element size and shape
4. Air velocity
5. Time of exposure of drop to aerosol.

Details of theory, analysis, apparatus, etc. will be presented in the final report on this research. In the interest of brevity, the present report is restricted to the major experimental results which have been obtained up to now.

Experimental Results and Discussion of the Results

Experiments were carried out using a suspension of polystyrene particles in water, dispersed through a Vaponephrin nebulizer. Polystyrene spheres with diameters of 0.814 μ, 1.171 μ, 1.8 μ, and 2.85 μ were used as aerosols and drops of water, glycerol, m-methoxy phenol and formamid served as collectors. The physical properties of the different collectors are given in Table 1. The results of these experiments are plotted in Figures 1 to 9 as

$$N_D = \left[\left(\frac{\rho_p \cdot U_o}{18 \cdot \eta_g} \cdot D_c\right)^{1/2} D_p\right]$$

vs. % collection efficiency. Figures 1 to 4 show that water drops have the highest collection efficiency for a given N_D, then come glycerol, m-methoxy phenol and formamid. Except for water the order of the others changes with particle size.

The results are less scattered in the case of small particles and of liquids having higher viscosities. The reason for the large scattering of the 2.85μ particles is the relatively low number of particles counted. In the case of liquids with lower viscosity (like water) the drops oscillated more violently at a certain given air velocity and in some cases there was shattering or migration of the drops.

The data for polystyrene particles were found to be not too reliable for the following reasons. Repeating experiments within time span of two or three months showed discrepancy between the first and the later results. The reason seems to be aging of the surface active agent present in the suspension. Another effect is discussed in an article by G. Langer and A. Liebman in the J. Coll. Sci. 15, 357--360 (60). In this article the authors point out that aerosols made from monodispersed polystyrene suspension are not really monodispersed. Dispersing 0.814μ particles diluted 1 to 100 (the same dilution that I used) gave in the aerosol a concentration of 109 par/cc. versus the calculated value of 2 par/cc., and 64% of the particles were larger than 1μ.

TABLE 1

PHYSICAL PROPERTIES OF DROPS USED AS COLLECTORS

Material	ρ gr/cm³	γ dyn/cm²	η C.P.
Water	0.996 at 27.5°C.	72.75 at 20°C.	0.89 at 25°C.
Glycerol	1.260 20/4	63.4	380 at 30°C.
M-Methoxy Phenol	1.1356 at 28° C.	83.1 at 20°C.	29.3 at 28°C.
Formamid	1.1292 25/4	58.2	3.27 at 25°C.

Figure 9 shows the results of experiments carried out to determine the influence of aging on the collection efficiency. Unfortunately, the particle size chosen (1.8μ) is less influenced by aging than the smaller particle sizes, so that the results don't deviate very much from former results. Comparing these curves to the curves for 1.8μ in Figure 3 shows that the efficiency of all the collectors dropped except for m-methoxy phenol. This means that aging of the surface active agent takes place in the original sample before diluting. The curves in Figure 9 show a minimum at low N_D. The reason for this minimum can be explained by the observation that

at low N_D (which means large drops and low air velocities) the drops are not fully above the supporting wire, their lower part is below the wire. Since this part has a high collection efficiency relative to the rest of the drop, the collection efficiency rises.

Comparing the collection efficiency of oscillating drops to that of Ranz and Wong data (Ind. and Eng. Chem. 44, 1371 (52) for stationary sphere (and this can be done only for 1.8μ and 2.85μ diameter particles) shows that the effect of oscillation is not substantial. On the other side the collection efficiency for 1.8μ particles for example at N_D = 0.32 is 5% for glycerol, 6% for meta-methoxy phenol, 12% for formamid and 21% for water vs. 13.7 for a stationary sphere. This seems to suggest that the influence of the interfacial tension between the particles and the collecting drop is a much more important factor than oscillation.

The polystyrene spheres are covered with a layer of surface active agent and may be even with a layer of water, thus a very low interfacial tension should be expected to exist between the particle and the water drop, and a high efficiency is expected. Glycerol and formamid which dissolve well in water should take the second place and m-methoxy phenol the last one. In Figure 9 we see that m-methoxy plenol takes the second place, probably because of the aging of the surface active agent. It is interesting to note that the aging of the surface active agent has the largest influence on the 0.814μ since here the larger deviations were measured, less on 1.171 and almost none on 1.8μ particles.

In Figures 1 and 2 one sees that the collection efficiency of formamid, m-methoxy phenol and glycerol (at least in the 0.814μ and 1.171μ particle sizes) takes the form of a set of almost parallel straight lines. No theoretical reason was as yet found to explain this relation. In general it can be said that in order to get better correlations, the Re and We groups, and the contact angle, or any other number characterizing the interfacial tension, should be introduced.

Before ending this paragraph there are some interesting effects that should be noticed. Comparing the efficiency with those obtained by Ranz and Wong, one sees that the 0.814μ and most of the 1.171μ curves are below the Ranz and Wong value of N_D for zero collection efficiency. These two curves can be presented as straight lines, while the curve for 1.8μ in most cases and for 2.85μ in all cases follow the exponential form of Ranz and Wong curve. This suggests that below N_D = 0.2 (which is equivalent to Ranz and Wong zero efficiency) another mechanism becomes important.

All of the present theoretical considerations seem to indicate that the interception or diffusion mechanisms are not expected to be appreciable above particle diameter of 0.2μ. It is difficult to assume that these effects are due to oscillation. Since oscillation velocities are low compared to particle velocities, it may be that the rippling of the drop's surface is the cause for this increase in collection efficiency with decreasing particle size below N_D = 0.2.

It is also possible that this phenomenon results from the surface active agent covering the particles since a decrease of collection efficiency is realized with aging especially in these particle sizes. Comparing the results with those expected from theoretical considerations show that the results lie between the collection efficiencies for a sphere and those for a disc, which agree with the deformation suffered by the oscillating drop.

A comparison of the results for the collection efficiency of glycerol drops shows that the efficiency increases with the time of the experiment. This may be due to accumulation of surface active agent on the surface of the glycerol drop, and a following decrease in interfacial tension. Again this phenomenon may be only a result of the aging suffered by the surface active agent.

An attempt was made to explain the results by constructing a mathematical model in which three forces are acting on the particle. The Van der Waals forces tending to capture the particle, and the surface tension and drag forces tending to carry the particle away. This model is still in a developing stage and no results can be reported as yet.

Conclusion

The data presented in Figures 1 to 9 are not reliable because of the aging of the surface active agent; nevertheless, they show certain trends.

1. It seems that the collection efficiency of the smaller particles is influenced much more by the aging of the surface active agent than that of the larger particles.

2. The interfacial tension seems to be the most important single factor affecting the collection of particles by drops. In all the experiments water shows the highest collection efficiency, glycerol, formamid and m-methoxy phenol comes next following this order in most cases.

3. An interesting phenomenon not as yet completely understood is the increase in collection efficiency with decreasing particle size below a certain N_D.

4. It seems that the We and Re groups and a number which is a function of interfacial tension should be included in the presentation of the results. Then one curve might correlate all the data.

5. The increasing collection efficiency with decreasing particle size and the change in the characteristic of the correlation below $N_D = 0.2$ seems to point toward a change in collection mechanism.

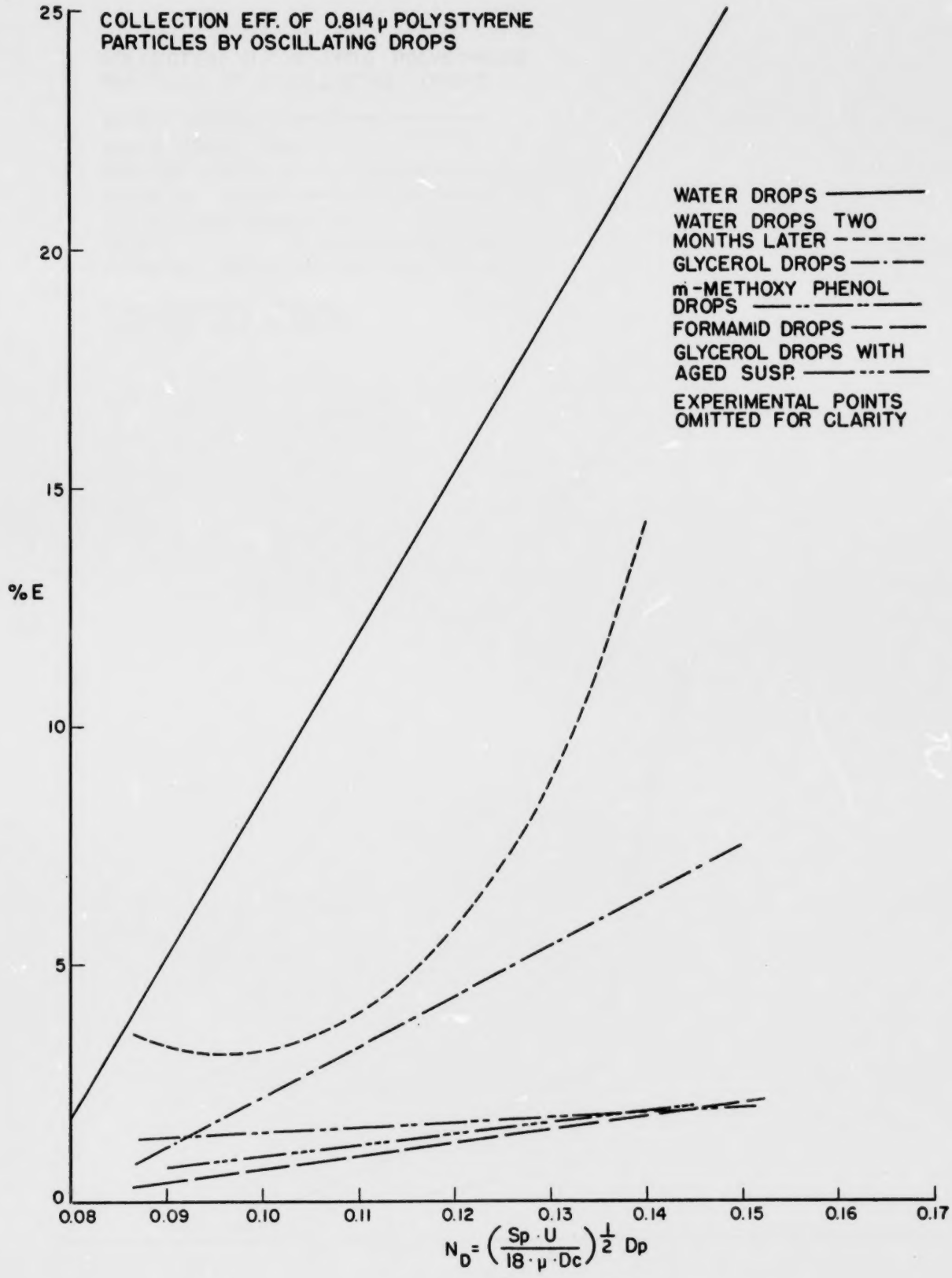
COLLECTION EFF. OF 0.814 μ POLYSTYRENE PARTICLES BY OSCILLATING DROPS
WATER DROPS
WATER DROPS TWO MONTHS LATER
GLYCEROL DROPS
m-METHOXY PHENOL DROPS
FORMAMID DROPS
GLYCEROL DROPS WITH AGED SUSP.
EXPERIMENTAL POINTS OMITTED FOR CLARITY
%E
25
20
15
10
5
0
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
$N_D = \left(\frac{Sp \cdot U}{18 \cdot \mu \cdot Dc}\right)^{\frac{1}{2}} Dp$

FIGURE 1-B

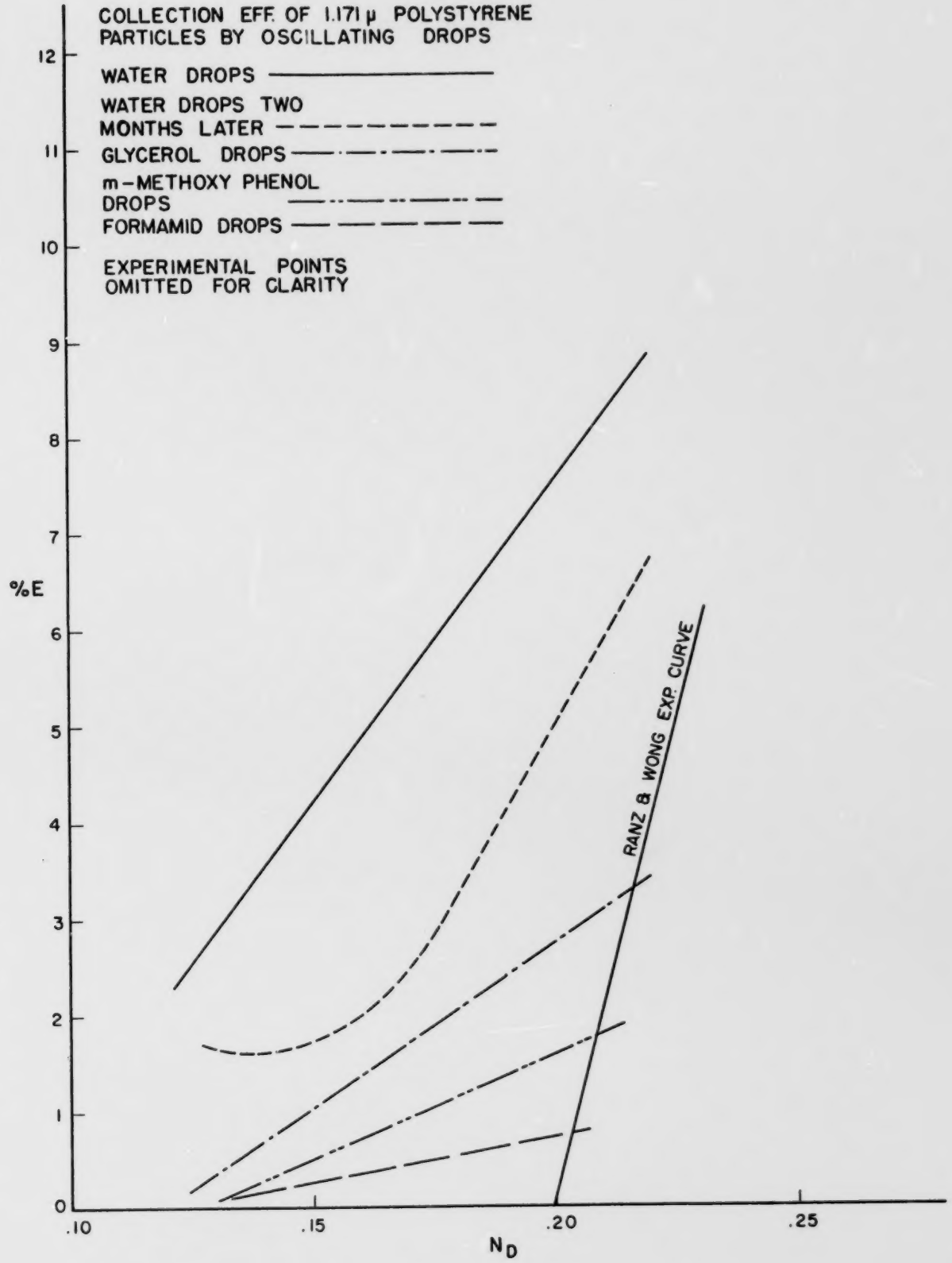
COLLECTION EFF. OF 1.171 μ POLYSTYRENE PARTICLES BY OSCILLATING DROPS
WATER DROPS
WATER DROPS TWO MONTHS LATER
GLYCEROL DROPS
m-METHOXY PHENOL DROPS
FORMAMID DROPS
EXPERIMENTAL POINTS OMITTED FOR CLARITY
%E
12
11
10
9
8
7
6
5
4
3
2
1
0
.10
.15
.20
.25
N_D
RANZ & WONG EXP. CURVE

FIGURE 2-B

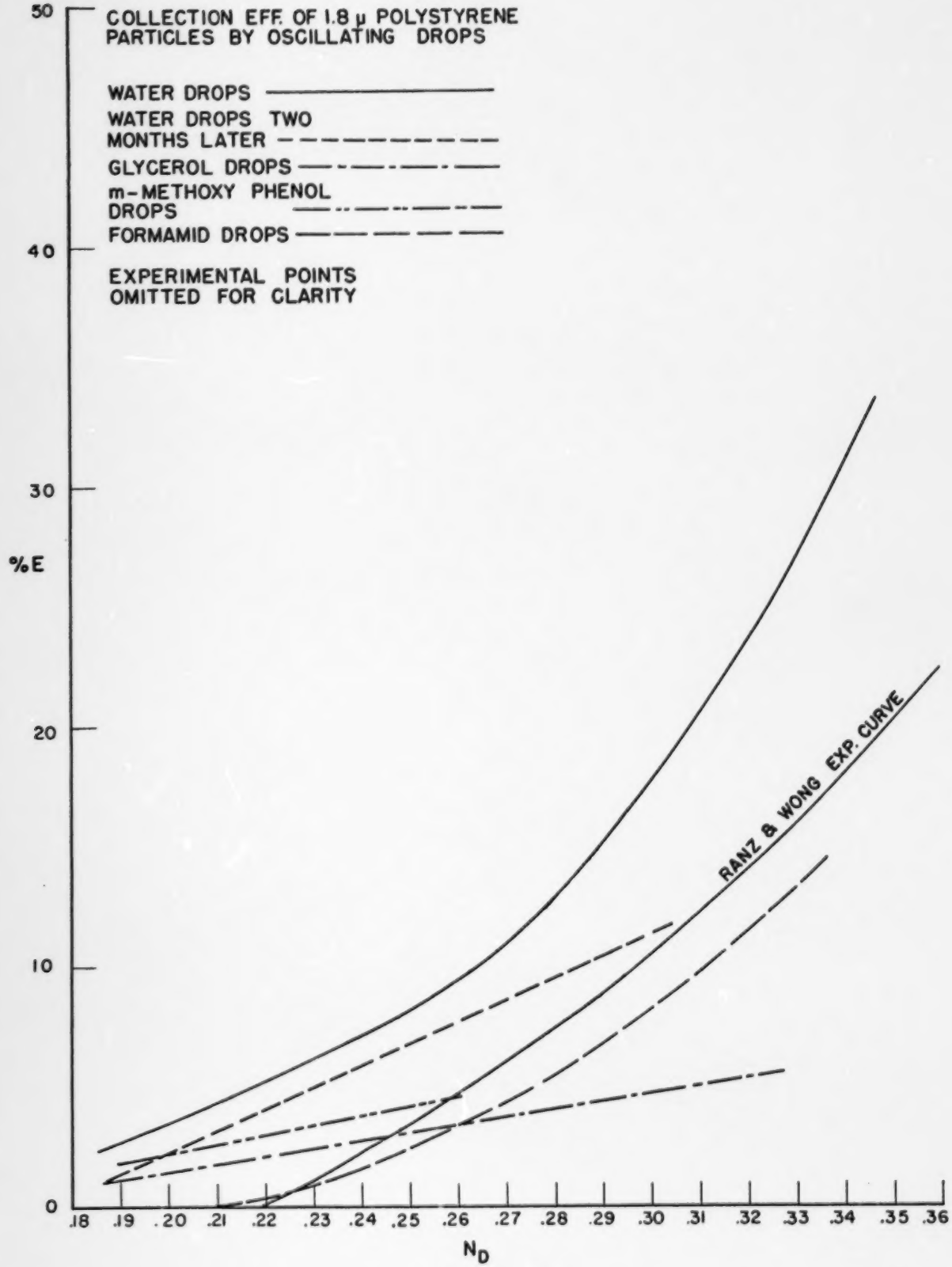
COLLECTION EFF. OF 1.8 μ POLYSTYRENE PARTICLES BY OSCILLATING DROPS
WATER DROPS
WATER DROPS TWO MONTHS LATER
GLYCEROL DROPS
m-METHOXY PHENOL DROPS
FORMAMID DROPS
EXPERIMENTAL POINTS OMITTED FOR CLARITY
RANZ & WONG EXP. CURVE
%E
50
40
30
20
10
0
.18 .19 .20 .21 .22 .23 .24 .25 .26 .27 .28 .29 .30 .31 .32 .33 .34 .35 .36
N_D

FIGURE 3-B

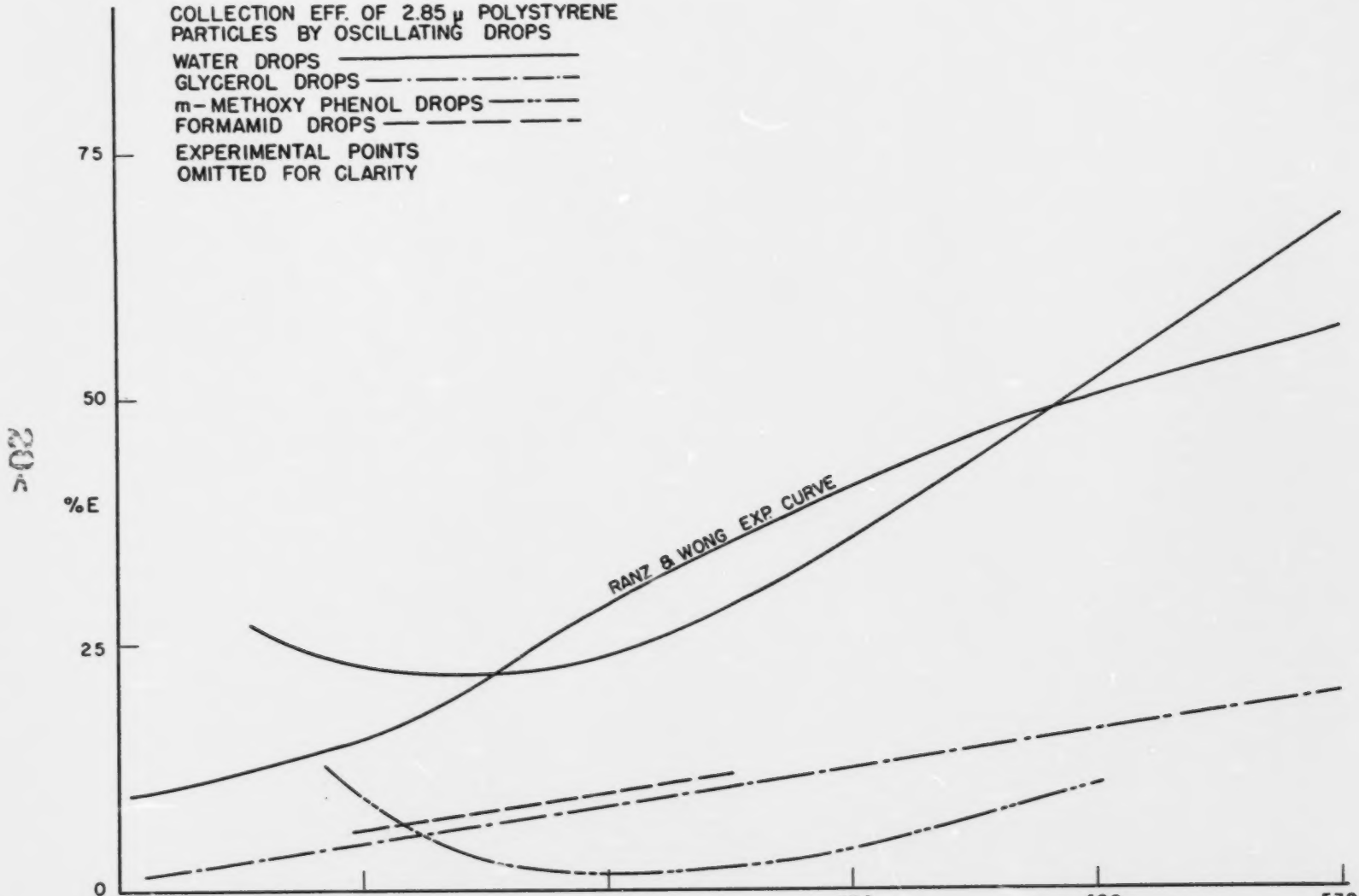
COLLECTION EFF. OF 2.85 μ POLYSTYRENE PARTICLES BY OSCILLATING DROPS
WATER DROPS
GLYCEROL DROPS
m-METHOXY PHENOL DROPS
FORMAMID DROPS
EXPERIMENTAL POINTS OMITTED FOR CLARITY
RANZ & WONG EXP. CURVE
%E
75
50
25
0
.280
.330
.380
.430
.480
.530
N_D

FIGURE 4-B

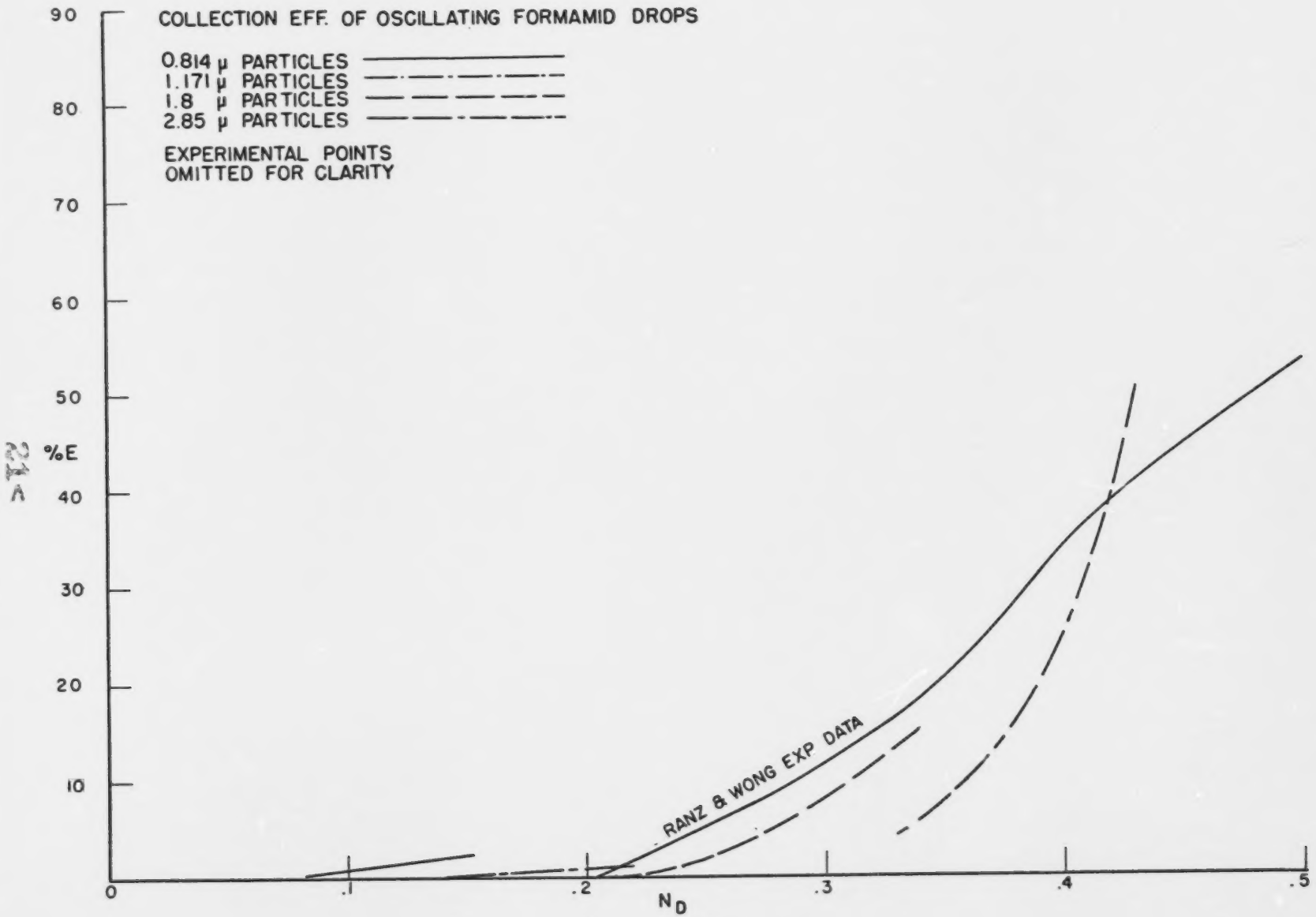
COLLECTION EFF. OF OSCILLATING FORMAMID DROPS
0.814 μ PARTICLES
1.171 μ PARTICLES
1.8 μ PARTICLES
2.85 μ PARTICLES
EXPERIMENTAL POINTS
OMITTED FOR CLARITY
90
80
70
60
50
%E
40
30
20
10
0
.1
.2
.3
.4
.5
N_D
RANZ & WONG EXP DATA

FIGURE 5-B

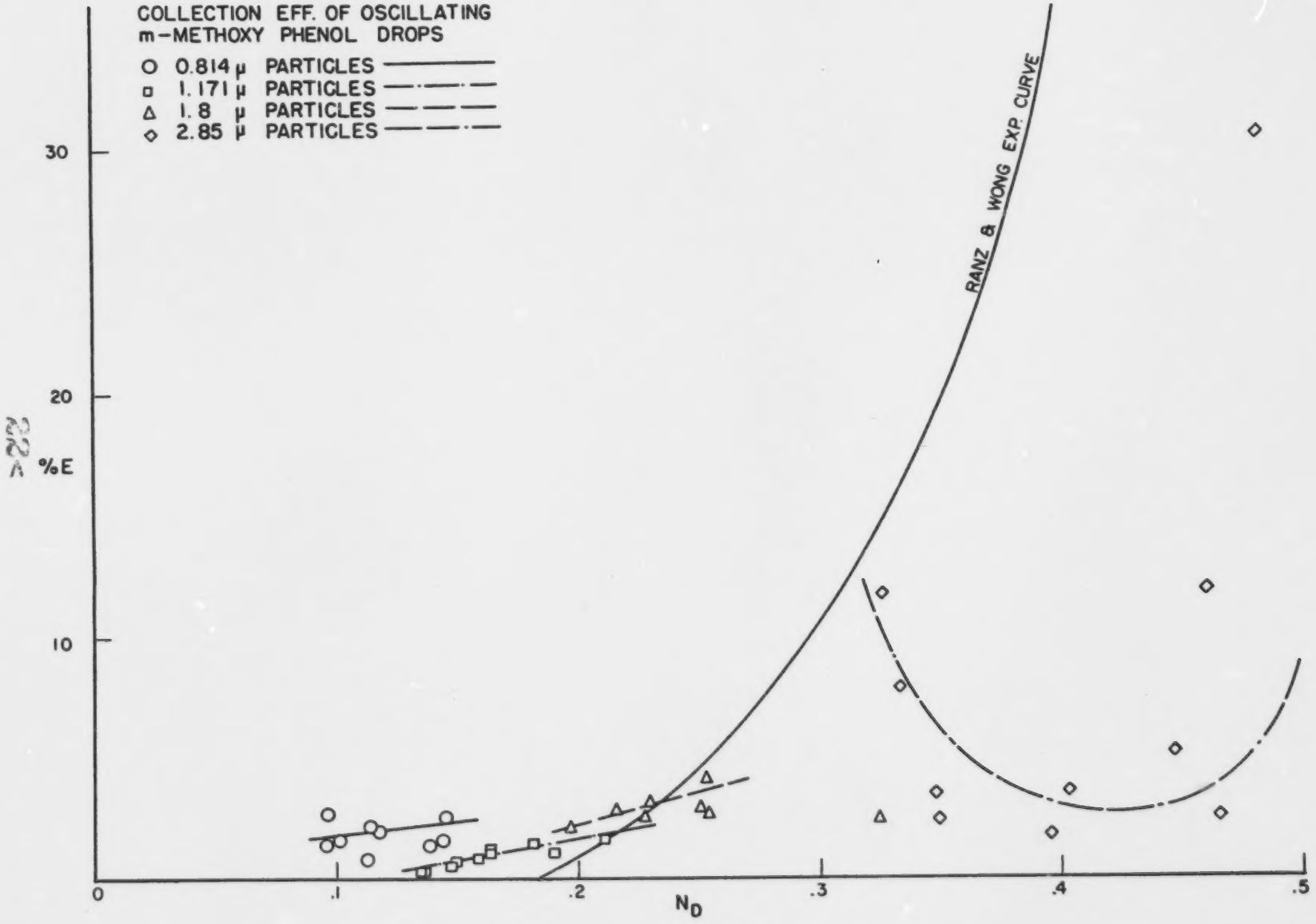
COLLECTION EFF. OF OSCILLATING
m-METHOXY PHENOL DROPS
O 0.814 μ PARTICLES
□ 1.171 μ PARTICLES
△ 1.8 μ PARTICLES
◇ 2.85 μ PARTICLES
RANZ & WONG EXP. CURVE
%E
30
20
10
0
.1
.2
.3
.4
.5
N_D

FIGURE 6-B

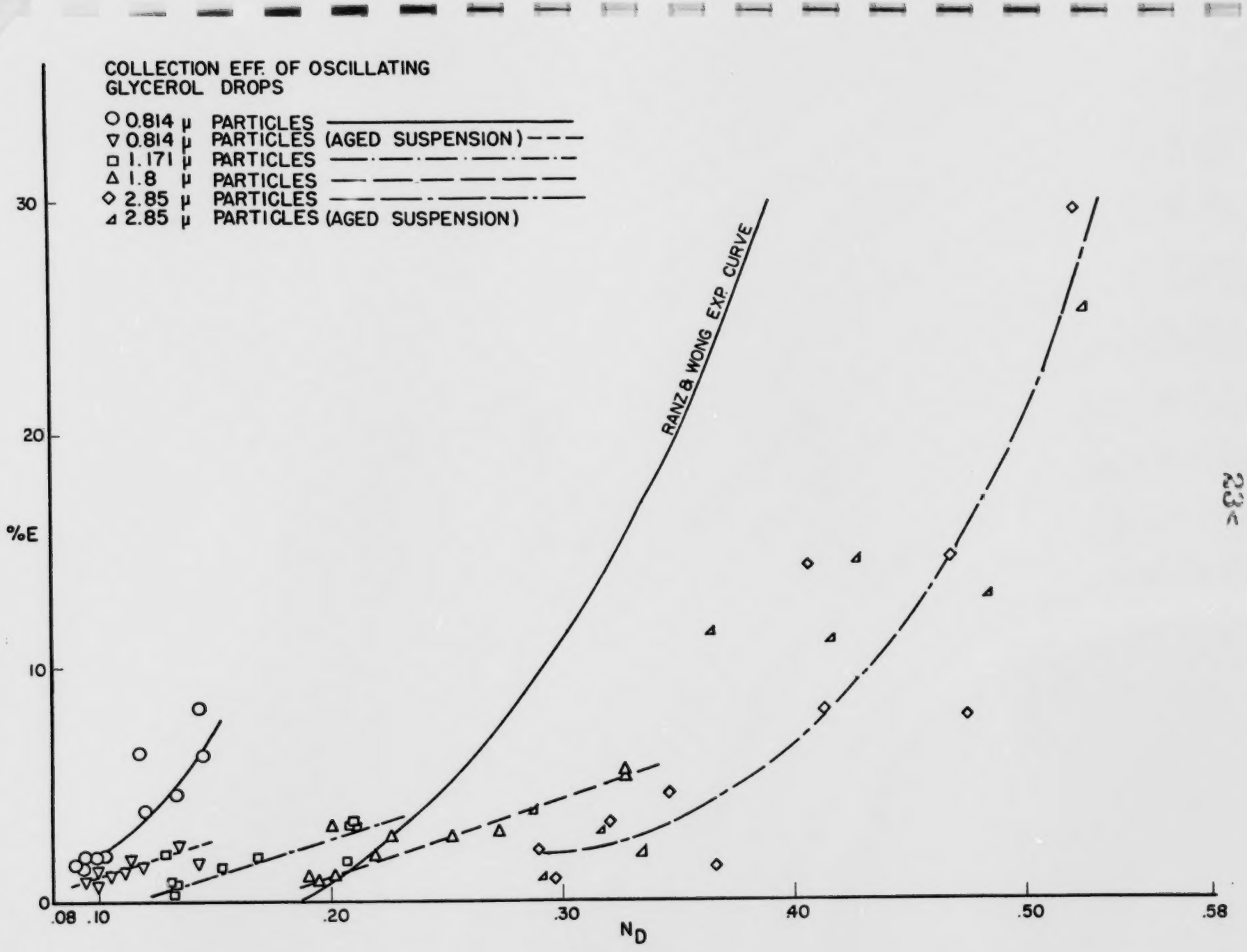
COLLECTION EFF. OF OSCILLATING GLYCEROL DROPS
○ 0.814 μ PARTICLES
▽ 0.814 μ PARTICLES (AGED SUSPENSION)
□ 1.171 μ PARTICLES
△ 1.8 μ PARTICLES
◇ 2.85 μ PARTICLES
◁ 2.85 μ PARTICLES (AGED SUSPENSION)
RANZ & WONG EXP. CURVE
%E
30
20
10
0
.08
.10
.20
.30
.40
.50
.58
N_D

FIGURE 7-B

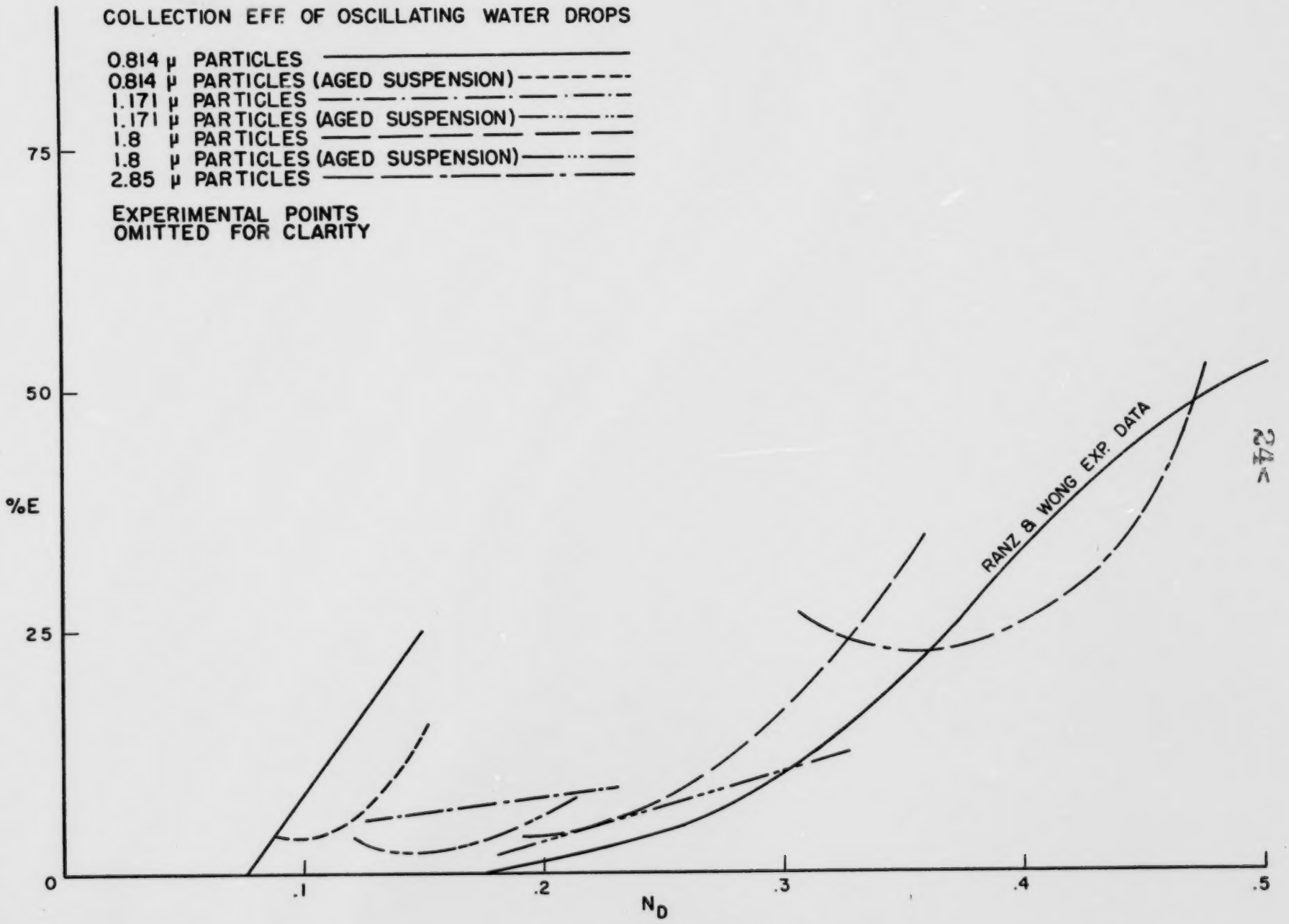
COLLECTION EFF. OF OSCILLATING WATER DROPS
0.814 μ PARTICLES
0.814 μ PARTICLES (AGED SUSPENSION)
1.171 μ PARTICLES
1.171 μ PARTICLES (AGED SUSPENSION)
1.8 μ PARTICLES
1.8 μ PARTICLES (AGED SUSPENSION)
2.85 μ PARTICLES
EXPERIMENTAL POINTS OMITTED FOR CLARITY
RANZ & WONG EXP. DATA
%E
75
50
25
0
.1
.2
.3
.4
.5
N_D

FIGURE 8-B

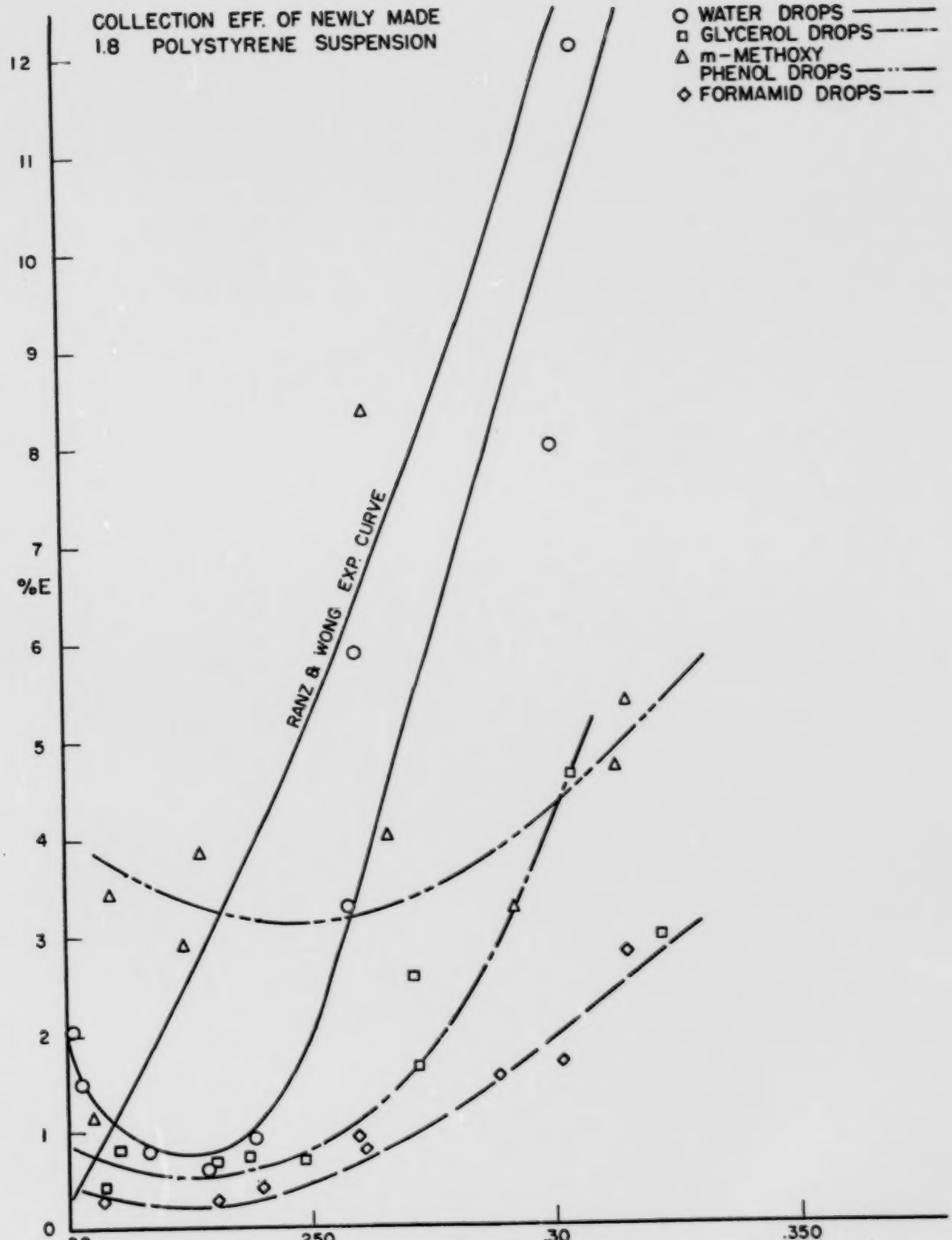
COLLECTION EFF. OF NEWLY MADE
1.8 POLYSTYRENE SUSPENSION
WATER DROPS
GLYCEROL DROPS
m-METHOXY PHENOL DROPS
FORMAMID DROPS
RANZ & WONG EXP. CURVE
%E
0
1
2
3
4
5
6
7
8
9
10
11
12
.20
.250
.30
.350
ND

FIGURE 9-B

APPENDIX C

Interim Progress Report on

PARTICULATE COLLECTION AND GAS ABSORPTION IN PACKED COLUMNS WHICH PROMOTE LIQUID OSCILLATION AND CIRCULATION

Fay Fun

Introduction

Gas absorption, in general, is carried out by employing a continuous phase and a dispersed phase in mutual contact. It is also very often conducted by dispersing the liquid phase. This is just one type of mass transfer operations between two phases, where a molecular species is transported from the gas phase into the liquid phase. This operation is of especial interest to us because it bears an obvious similarity with the scrubbing of very fine dust particles by a liquid stream. The only difference between them is that in the later operation, dust particles instead of molecules is the the diffusing or transporting component. However, it was noted (5) that, for fine particles in the submicron range, diffusional mechanism as a result of random Brownian motion is the predominating mechanism. Therefore,we postulate that a good, efficient gas absorption equipment may prove to be also an effective dust scrubbing device for fine submicron particles.

Consider first the situation of transport of material from a continuous gas phase into a single dispersed liquid body. Most theoretical approaches to this problem have been based on molecular diffusion within the body and that the interior of the body is stagnant or in streamline motion (7). Yet many investigators have also either observed motion of fluid inside the dispersed body and oscillating of the body as a whole, or predicted the existence of these motions theoretically (1, 2). The argument is that owing to the gravitational force of the body itself, the varying interfacial tension of the fluids, the skin friction and unsteady forces exerted by the continuous phase, the body as a whole and the interior of the body must be in motion. For low rates of flow and very large liquid body, these motions are rather unimportant. But in many instances, it was reported that oscillation and internal circulation had an appreciable effect on the rate of absorption (3). The effect of these motions is believed to be higher at higher rates of flow for smaller dispersed liquid bodies.

Previous studies of packed columns indicate that for a given liquid rate, both gas phase controlling and liquid phase controlling systems exhibit an increased absorption efficiency at increased gas velocities beyond loading point. This fact was reported in literature as decrease of HTU (8) or increase of Ka (6). As yet the performance between loading point and flooding point has not been fully investigated. It is not certain whether this improvement of mass transfer is simply due to an increase in the wetted area of packing caused by gas pressure drop, a rippling

of the liquid surface, or a more serious disintegration of the liquid streams. It will suffice to say, however, that more vigorous mixing and contacting can be achieved at near flooding point. It is also noted that while liquid rate increases absorption efficiency steaily over the whole range of rates, the gas rate only increases the efficiency at rates above loading point. A more close examination of this phenomena suggests that the increase of efficiency may not only be caused by the more vigorous and increased contact, but also caused by the upward lifting force of the gas which probably keep the liquid elements in suspension for a prolonged period of time, so that more solute is transferred to each liquid element than as below loading point. The coupled effect of this momentary suspension of the liquid element and its subsequent shattering and recoalescence is then the result of increasing efficiency.

In the study of single drop spray columns, it was observed that the percentage absorption or extraction during drop formation and coalescence is often of considerable importance (7). On an HTU basis, the HTU at formation and coalescence is several times smaller than that could be obtained by the main section of absorption column. As a conclusion, the mechanism of formation and coalescence should be a much more effective means of transfer than simply moving the drop through a certain length of column. It is easy to perceive the high efficiency at formation from a qualitative theoretical standpoint. During drop formation, there are several mechanisms occurring simultaneously: (a) the expansion of the drop volume, (b) the circulation of fluid inside the volume, (c) the "skin" of the drop being constantly renewed by fresh fluid and (d) since the drop is subject to the flow of another phase around it, the oscillating of the drop as a whole. Each one of these mechanisms has been studied and reported to be helpful for mass transfer. Therefore, at least theoretically, the formation mechanism is undoubtedly a very effective means of transfer between two phases.

In summarizing the above ideas we now see a number of mechanisms which seem to be very effective and powerful means for improving absorption efficiency. To study all of these mechanisms individually is very difficult both theoretically and experimentally. Because it is not possible to separate the effect of one from the other, we propose to study a contacting system in which every one of the following mechanisms is believed to occur to some extent:

(1) Internal circulation of fluid inside a dispersed body
(2) Oscillation of the body as a whole
(3) Shattering of the body by gaseous thrust
(4) Splashing of the body by impact to solid surface
(5) Collision between bodies
(6) Coalescence of small bodies

Aerosol Scrubbing

Three mechanisms have been observed to account for the collection of dust by liquid. They are inertia, impingement and diffusion. Depending on the size of dust particle, each one of these mechanisms

has its range of predominance. For particle size below 5μ, it was reported that diffusion mechanism begins to be significant for the transfer process and below 1μ, the transfer is almost entirely controlled by the diffusional properties of the system (5, 9). Hence, for submicron particles, the argument for gas absorption stated before will be expected to be directly applicable to dust scrubbing. The diffusivity of dust particles may be estimated from the Stokes-Einstein equation with Cunningham correction factor (5),

$$Dg = \frac{KT(1+1.72\lambda/d)}{3\mu_g \pi d} = \text{Diffusivity in gas phase}$$

where K = Boltzman constant 1.37×10^{-8} erg/°K
T = absolute temperature °K
λ = mean free path of gas molecules
d = diameter of aerosol particle
μ_g = viscosity of gas

also:

$$D_l = \frac{KT}{+ 3\pi\mu_L d} = \text{diffusivity in liquid phase}$$

However, for larger particles, the other two mechanisms come into the picture and become significant. They should also be given proper consideration for the overall particle scrubbing process.

When a dust laden aerosol flows past a liquid droplet, normally the particles will follow the streamlines of the gas and go around the droplet without effecting any removal. But the droplet may still catch some portion of the particles in the aerosol, if (a) the particle is heavy enough, so that inertia forces keep it moving away from the streamline and reach the surface of the droplet, (b) the particle is of size in the order of half that of the droplet so that the particle carried by the streamline may touch the surface of the droplets, (c) the particle is small enough so that the random Brownian motion will carry the particle away from the streamline and reach the surface of the droplet. These are so termed as the inertia, impingement and diffusional effect.

Internal circulation of fluid inside a dispersed body will help to bring any particles reaching the surface of the drop into the inner core of the drop. In so doing, a fresh surface will appear which may be more effective in collection. Oscillation of the liquid body has been studied by Goldshmid and Constan and appears to have a small effect on both collection via the inertial mechanism and gas-phase mass transfer in the range studied. It may be, however, that operation at the higher drop sizes and air velocities envisioned for this study will provide conditions for increased efficiencies.

Shattering of the liquid body by gaseous thrust is very effective in improving diffusional effect as discussed before. In so doing, the drop disintegrates into smaller drops which are less effective for inertia and impingement collection (ref. 9). But the shattering and splashing of smaller drops also helps sweeping the gap

between original drops so that more collision will be expected. Splashing by impact on solid surface should give comparable effects.

Collision between bodies is an intermediate step in effectuating the other mechanisms. When two liquid drops collide, the resulting drop may further disintegrate into still smaller drops or may oscillate for a short period and coalesce. In the latter case, the process also increases internal circulation. Direct effect on collection may be increased sweeping area and momentarily increased collector size.

General Objectives

The primary purpose of this research is to examine the possibility of utilizing the postulated mechanisms in the operations of gas absorption and aerosol scrubbing and to study the operational characteristics of such an equipment. Comparison of mass transfer and diffusional collection in the same type of equipment may provide a basis for a generalized treatment of both operations.

Experimental work will cover the following:

1. Study constructional variables, such as geometry of packing, packing material, etc.

2. Study dynamical variables, such as flow rates, pressure drops and flooding, etc.

3. Collect data for comparing molecular diffusion and particle collection in the same equipment under similar operating conditions.

Description of Equipment

The experimental apparatus consists essentially of a column which is made of 4-inch I.D. glass pipes with tees on each end for introducing and withdrawing the streams. The assembly is interchangeable to facilitate either co-current or counter-current operation and also to permit the diversion of aerosol flow to a nozzle to be used for single element studies. Single packing element can be suspended above the nozzle. When single liquid drop is placed on the piece of element, the flat velocity profile of the nozzle may permit observation of the drop under various gas rates. This setup is used to obtain any supplementary information needed concerning a liquid droplet on a packing element.

The packing section is a stacked assembly of parallel elements separated by spacers. It is similar to conventional grid packing although it differs in that for each grid it provides large top to side ratio. With this kind of packing, the fractional void space, (ϵ), can take on a higher value and hence a smaller Ap/ϵ^3 value. (Ap is the specific surface.) Since pressure drop for dry packing is proportional to and flooding velocity is inversely proportional to Ap/ϵ^3, smaller Ap/ϵ^3 means smaller pressure drop and higher flooding velocity. Therefore, the test column is expected

to have greater capacity.

The choice of packings of this type is justified for incorporating about the six mechanisms discussed above. With a large a/b ratio, the liquid accumulates on top of a grid where it is under the thrust of an unsteady state gas force, its own weight, surface tension and drag forces. Therefore, the droplet will be oscillating with internal circulation. At the same time, more liquid joins in as droplets from the plate above as well as from splashing and shattering of liquid bodies on the adjacent and lower grids. In so doing the liquid body grows larger and larger until it is shattered by the dynamical forces imposed on it and swept off the grid as smaller droplets.

Experiment

The chemical systems to be used for gas absorption are CO_2-Air-H_2O and NH_3-Air-H_2O. The former is chosen to study the case where liquid phase resistance controls and the latter for gas-phase-resistance-control. In order to assure that a purely gas phase controlling system is obtained, the liquid phase of the ammonia system may contain small amount of acid. Alternately the overall gas phase resistance can be corrected for liquid phase resistance in the ammonia system through the use of carbon dioxide absorption data. In this way, a pure gas phase resistance can also be calculated. The aerosol systems will probably be metal oxide fumes.

Present Status and Future Plans

At this time the general layout is almost completed. Immediate plans are to test the performance of the whole system and to calibrate meters. The gas absorption part of the experiment will be carried out first. While in so doing, the equipment for generating aerosols will be developed and constructed. The whole experimental work is expected to be completed next summer.

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"Appendix D"

Collection of Small Particles in Baffled Conduits

Ralph Hodous° and Seymour Calvert

Case Institute of Technology

Small particles may be removed (or collected) from a suspension in a fluid by means of inertial force caused by the acceleration of the particles relative to the fluid. This mechanism of inertial collection is generally effective for particles larger than about 1 micron diameter and has been utilized in devices such as cyclone collectors and low density fibrous filters. One method of providing the acceleration necessary for inertial collection is to force the fluid stream to change its direction of flow as is done in the two devices mentioned above. Another method which has not been exploited previously is to utilize the secondary flow patterns which exist in certain fluid flow systems.

Secondary flow patterns are those which are not coincident with the major direction of flow of the fluid and which are consistent in their orientation and direction. Such patterns occur in flow through non-circular conduits, through bends and helixes, around obstructions, and other systems. The motion of the fluid in the secondary pattern is generally rotational although the streamlines are not necessarily circular.

Objectives

The research reported here is concerned with the collection of particles in baffled conduits. The secondary flow patterns, or eddies, form behind baffles which are perpendicular to the major fluid flow direction act as a series of cyclone collectors.

The geometric arrangement studied consisted of a rectangular duct with baffles mounted on one of the long interior walls. While many geometric variations can be envisioned, this arrangement is simple to construct and provides the essential features of the general baffled conduit system. The system was run as a dry aerosol collector although it could also be employed as a wet collector or on a liquid system as a thickener.

Mathematical Representations

The major collection mechanism in the baffled conduit is that due to the centrifuge effect of a series of rotating eddies. Particles which are transferred from the main stream of fluid to an eddy

°Present address - Standard Oil of Ohio

will move radially outward at velocities such that the centrifugal force is equal to the opposing fluid drag force. Those particles which move far enough will strike the baffle walls and presumably be collected.

In setting up this mathematical model the following assumptions are made:

1. There is instantaneous mixing of particles within the main fluid stream and between the main stream and the adjacent eddy.
2. The eddy is circular and its diameter is equal to the spacing between baffles.
3. The particles reach their terminal velocities in the centrifugal force field instantaneously.
4. All particles which strike a solid boundary will stick to it.
5. Terminal velocities may be approximated by Stoke's Law.

The drag force acting on a particle is given for laminar flow by Stoke's Law:

$$F = 3\pi\mu \, d_p \, u \qquad (1)$$

The terminal settling velocity, u_o, for a particle obeying Stoke's Law in a gravitational force field is given by equation 2. If the particle is

$$u_o = \frac{d_p^2 g \, \rho_s}{18\mu} \qquad (2)$$

now considered to be in a centrifugal force field at a distance r_c from the center, and has a tangential velocity u_t, the radial settling velocity is given by equation 3 where $\frac{a_c}{g}$ is the ratio of the

centrifugal acceleration

$$u_r = u_o\left(\frac{a_c}{g}\right) = \frac{u_o u_t^2}{r_c g} \tag{3}$$

to the acceleration due to gravity.

It will be assumed that the particles will be collected from the eddy only about 3/4 of its circumference, with transfer of particles from the main stream to the eddy occurring in the remaining 1/4 of its circumference. Equation 4 represents the time required, t_c, for the eddy to make

$$t_c = \frac{3}{4}\left(\frac{2\pi r_c}{u_t}\right) \tag{4}$$

3/4 of a revolution.

The distance, δ, a particle travels in time t_c can be found by multiplying t_c by the radial velocity of the particle, and is given by equation 6.

$$\delta = u_r\, t_c \tag{5}$$

$$\delta = \frac{3\pi}{2g}\left[u_t u_o\right] \tag{6}$$

The radial and tangential velocities of the particle are assumed to be independent of radius and it will be seen that this is valid because of the small distance travelled by a particle during 3/4 revolution. It is interesting to note (see equation 6) that baffle spacing should have no direct effect on δ.

From the δ corresponding to any one value of particle diameter the volume of eddy fluid cleaned per unit time, V_c, can be determined where B is the collector width in equation 7.

$$V_c = \delta u_t B = \frac{3\pi}{2g}\; u_o (u_t)^2 B \tag{7}$$

The collection efficiency of an individual eddy will be defined as the ratio of the rate of particle collection by the eddy to the rate of particle flow through the total cross section at this point in the apparatus and since the concentrations in the eddy and the mainstream are assumed to be equal,

$$E^\circ = \frac{N_c}{N_t} = \frac{V_c}{V_t} \tag{8}$$

By substituting equation 7 into 8 and by expressing V_t in terms of a linear gas velocity and the physical dimensions of the system;

$$E^\circ = \frac{3\pi u_o (u_t)^2}{h\bar{u}} \tag{9}$$

If K is defined to be the ratio of the average linear velocity of the main stream to the tangential velocity of the eddy,

$$E^\circ = \frac{3\pi}{2g} \frac{u_o \bar{u}}{h K^2} \tag{10}$$

If u_o, the terminal settling velocity, is replaced by its Stokes' Law equivalent (equation 2) the final form for the individual collection efficiency is represented by equation 11.

$$E^\circ = \left(\frac{\pi d_p^2 \rho s}{12\mu}\right)\left(\frac{\bar{u}}{h K^2}\right) \tag{11}$$

It remains to define the mathematical relationship between E° and the overall collection efficiency, E, of a series of eddies.

The overall efficiency for n baffles is defined by equation 12.

$$E = \frac{N_i - N_o}{N_i} \tag{12}$$

and

$$N_o = N_i (1-E^\circ)^n \tag{13}$$

So:

$$E = 1-(1-E^\circ)^n \tag{14}$$

Equation 14 represents the desired relationship between overall

collection efficiency and individual eddy efficiency.

Efficiency for a Distribution of Diameters

The equations developed up to this point define the collection efficiency for particles of a unique diameter. In order to relate the mathematical model to the real experimental system it is necessary to define efficiency for an aerosol which contains a range of particle diameters. Because the particle concentrations were determined by light scattering measurements in these experiments, the necessary relationships are more conveniently developed in terms of scattering cross-section rather than weight or number of particles.

The total scattering cross-section per unit volume, A_o, of the test aerosol is defined by equation 15.

$$A_o = \int_{(d_p)_1}^{(d_p)_2} \left(\frac{\partial A_o}{\partial d_p}\right) d\,(d_p) \qquad (15)$$

The fraction of scattering area penetrating the collector for any particle diameter, $(P_t)_i$, for n baffles is given by equation 16 where γ is a constant depending only upon the physical system and the average

$$(P_t)_i = 1-E_i = (1-E_i^o)^n = (1-\gamma d_p^2)^n \qquad (16)$$

linear gas velocity.

The total penetrating area can be found by integrating equation 17

$$A_p = \int_{(d_p)_1}^{(d_p)_2} (P_t) \left(\frac{\partial A_o}{\partial d_p}\right) d\,(d_p) \qquad (17)$$

The experimental overall collection efficiency measured with the light scattering photometer is given by equation 18. Theoretical values for A_o and A_p have been developed by consideration of the

$$E_A = 1 - \frac{A_p}{A_o} \qquad (18)$$

particle size distribution (equations 15 and 17), and can be substituted into equation 19 to determine the theoretical overall

$$E_A = 1 - \frac{\int_{(d_p)_1}^{(d_p)_2} P_{(t)} \left(\frac{\partial A_o}{\partial d_p}\right) d(d_p)}{\int_{(d_p)_1}^{(d_p)_2} \left(\frac{\partial A_o}{\partial d_p}\right) d(d_p)} \qquad (19)$$

collection efficiency based on scattering cross-section.

If A_o^1 is the fractional rather than total scattering cross-section, undersize the integral in the denominator of equation 19 is identically equal to one. Making this substitution results in equation 19a.

$$E_A = 1 - \int_{(d_p)_1}^{(d_p)_2} (P_t) \left(\frac{\partial A_o'}{\partial d_p}\right) d(d_p) \qquad (19a)$$

EXPERIMENTAL PROCEDURE

A titanium dioxide aerosol was produced by contacting tetra-isopropyl titanate vapors with moist air, then diluted with dry filtered air, and then run through the collector. The inlet and exhaust concentrations in the aerosol were measured with a light scattering photometer. Figure 1 is a schematic diagram of the apparatus.

The particle size distribution of the aerosol was determined by collecting a sample with an electrostatic precipitator and subsequently preparing a photomicrograph of the sample with the electron microscope.

Aerosol Generation

All of the experimental work was done using a system designed to produce a titanium dioxide smoke from tetra isopropyl titanate. A second system, a LaMer-Sinclair generator was tried on several occasions but could not generate an aerosol dense enough for light scattering measurements.

The physical system for generating the titanium smoke is shown

in Figure 2 (the values indicated are approximate operating conditions). Dry filtered air was blown over hot tetra isopropyl titanate and became saturated with vapor. It then passed up through a heated glass column where it was contacted with warm moist air causing the formation of a titanium dioxide smoke. The smoke was diluted with dry filtered air and passed through the test equipment.

The ethyl and n-butyl esters of titanium proved to be inferior to tetra isopropyl titanate. The ethyl ester was far too reactive to be handled conveniently, and the n-butyl ester has such a low vapor pressure that an excessive pot temperature (200°C) was required to produce a smoke of sufficient density.

Measurement of Aerosol Particle Concentration

A light scattering photometer designed by Mr. Yhuda Goldshmid (see Figure 3) was used to determine the particle concentration of the test aerosol. A sample of the aerosol was drawn through a glass tube in the photometer and a beam of monochromatic light was passed through the aerosol. A photomultiplier tube, along with a photomultiplier microphotometer, was used to determine the intensity of the light scattered in any angle.

The light scattering photometer was calibrated directly from the experimental data. Plots of percent light transmission versus relative particle concentration (N/n_o) verified that the amount of light scattered to the photomultiplier tube is directly proportional to the total cross-sectional scattering area per unit volume of aerosol.

For the range of particle sizes of interest here, the effective scattering cross-section may be approximated as being a constant multiple of actual particle cross-section. The photomultiplier microphotometer readings may be used directly to calculate the overall collection efficiency, because in the ratio of cross-sections (see equation 18) the constant would cancel out.

The Experimental Procedure

The experimental start-up procedure consisted of adjusting the variacs connected to the various heaters, and the air flow rates through the generator to their proper valves and allowing the system to attain equilibrium, and remain at equilibrium for fifteen minutes to insure that an aerosol was obtained whose properties would not vary with time.

A sample was then collected with an electrostatic precipitator manufactured by the Mine Safety Appliance Company (CT-48295) for particle size distribution analysis under the electron microscope. The generator was then connected to the test collector and the required data were obtained using the light scattering photometer. The pressure drop at various flow rates was also determined. The collector was washed with water after each run.

The Experimental Collector

The experimental collector (see Figure 4) was a rectangular conduit approximately six feet long and four inches wide with provisions for varying the depth from seven-eighths to two inches. The top and both sides were constructed from one-half inch thick plexiglass while the floor plate was cut from aluminum sheet. The baffles were cemented to the aluminum floor plate and provisions were made for the aerosol sample probe and pressure drop taps.

Five different floor plates were built to be used with the conduit and their specifications can be found in Table I.

TABLE I

FLOOR PLATE SPECIFICATIONS

Plate	w/s	w(in.)	n	Cutout	Length (in.)
1	1.0	1-1/8	44	Square	55.5
2	1.0	11/16	73	Square	55.2
3	1.0	1/4	146	Square	55.2
4	2.3	21/32	140	Rectangular	52.5
5	0.86	7/8°	55	Semi-circular	55.2

°diameter

Each floor plate, except plate 4, was run using at least two values of h (height for flow above baffles).

RESULTS

The basic experimental results are data on collection efficiency and pressure drop. Figure 5 shows collection efficiency based on particle area versus average air flow rate with average TiO_2 particle size as a parameter for baffle plate No. 2 with h = 1/8 inch. Figure 6 shows pressure drop per foot of baffled conduit versus air velocity with height over baffles (b) as a parameter for plate No. 2.

The pressure drop data can be represented more concisely in terms of the constant "K" in equation 11 and the constant "b" in the empirical equation 20.

$$\Delta P = b(\bar{u})^{1.7} \qquad (20)$$

Although "K" was introduced to represent the ratio of average main stream velocity to eddy tangential velocity it becomes the receptacle for any errors in the model because eddy tangential velocity was not measured experimentally. Values for this constant were computed for each experimental point by means of equations 11, 16 and 19. Each geometric arrangement can be characterized by an average K (or K^2) as shown in Table II. No significant dependence of K on air velocity

TABLE II

AVERAGE VALUES OF K^2 AND b FOR

DIFFERENT SYSTEM GEOMETRIES

Plate	w	h	$\bar{K}^2$	b x 10^3
1	1-1/8inch	1/8inch	11.4	4.34
1	1-1/8	3/16	11.5	2.65
2	11/16	1/8	9.7	4.72
2	11/16	3/16	11.5	2.87
2	11/16	5/16	14.9	1.35
3	1/4	1/8	40.4	2.52
3	1/4	1/4	40.4	1.17
4	21/32	1/8	33.0	
5	7/8	1/8	32.7	6.13
5	7/8	5/16	20.3	1.12

was found for velocities up to 60ft./sec. nor on particle diameter in the range of .29 to 1.24 microns.

Pressure drop data are represented by means of the constant "b" (in equation 20) for which values are given in Table II. In all cases studied the pressure drop was proportional to air velocity raised to the 1.7 power. It should be noted that equation 20 is a dimensional representation and that pressure drop is in inches of water per foot of baffle and air velocity is in ft./sec.

Particle diameters are represented as average effective diameter which is defined as that diameter which would have the same collection efficiency as that for the entire size distribution. These were computed by means of equations 16 and 19. The particle size distributions were unique in that the cross-sectional area in any size range was independent of size. Figure 7, a plot of percent of particle area undersize versus particle diameter, shows the size distributions for one run.

Conclusions

The experimental data indicate that the collection efficiency equations represent the real system quite well within the ranges of variables studied. The values of K^2 computed from the data are reasonable and do not vary significantly with particle size. Roshko (ref. No. 2) found that K^2 is approximately 10.0 for w = 4 inches, w/s = 1.0, h = 36 inches, and $\bar{u}$ = 75 ft./sec. This agrees in magnitude with the values obtained for plates 1 and 2. The high value of K^2 for plate 4 may be explained on the basis of additional friction due to the high ratio of baffle height to spacing. The reasons for the high value of K^2 for plate 3 is not apparent from the facts at hand. For plate 5 the high value of K^2 may be due to higher re-entrainment from the circular baffle pockets than from the rectangular

pockets of the other baffle plates.

The use of Stoke's Law to describe particle motion is shown to be acceptable by the facts that K^2 does not vary with particle size and that collection efficiency is proportional to the square of particle diameter. This latter fact was established by comparing runs made with aerosols with different average diameters and thereby also justifies the use of equation 16 in computing the efficiency for polydisperse aerosol.

The relationship between pressure drop and air flow rate is well represented by equation 20. The relationship may alternatively be given in terms of a friction factor-Reynolds number plot. While this manner of treatment of the data yields a family of smooth curves dependent on h and w, there is no uniform progression of curves according to such parameters as the ratio of h/w. The order of magnitude of the friction factors is in reasonable agreement with the value of about 0.03 given by Knudsen and Katz (ref. No. 1). Mean values of Fanning friction factor for plate 2 are 0.06 at a Reynolds number (based on diameter equal to 2 h) of 1,800, 0.04 at 4,000, and 0.03 at 10,000.

With regard to practical application of baffled conduits for particle collection, this exploratory study indicates that they have properties as good as, and in some respects better than presently employed devices. The collection efficiency-power requirement relationships for the baffles studied compare favorably with those presently used for gas scrubbers. Figure 8 is a plot of number of transfer units ($\ln \frac{1}{1-E}$) versus horsepower required per thousand cubic feet per minute of air for several values of particle size and h in plate No. 2. High collection efficiency can be attained in the 1 or 2 micron size range, which is superior to cyclone performance. Further investigations of both mass transfer and particle collection in wetted baffle conduits are now in progress and will provide the additional information necessary for the engineering evaluation of baffled gas scrubbers.

This investigation was supported by a research grant (S-84) from the U.S. Public Health Service.

DEFINITIONS OF SYMBOLS

a_c	Centrifugal acceleration, ft /sec^2
A_o	Total inlet scattering cross section per unit volume of air-particle mixture, ft^2/ft^3
A_p	Total outlet scattering cross section per unit volume of mixture ~~for particles~~, ft^2/ft^3
A_o^1	Fraction of total cross sectional area per unit volume smaller than a given diameter, ft^2/ft^3
$\bar{d}_p$	Average effective particle diameter based on E_a, ft.
d_p	Particle diameter, ft.
E	Overall particle fractional collection efficiency
E_a	Overall fractional collection efficiency based on area for unique d_p.
E°	Particle collection efficiency of a single eddy for unique d_p.
F	Stoke's Law drag force, lb.
g	Gravitational constant, 32 ft/sec^2.
h	Free height for flow above baffles, ft.
K	Ratio of main stream velocity to tangential velocity of the eddy.
n	Number of eddies.
N_c	Number of particles collected per eddy per unit time, 1/sec.
N_t	Number of particles passing through cross section over eddy per unit time, 1/sec.
N_i	Number of particles per unit volume entering collector, 1/ft^3.
N_o	Number of particles per unit volume leaving collector, 1/ft^3.
$\Delta P_{f/L}$	Pressure drop per foot of baffle length ("H_2O/ft.)
$(P_t)_i$	Fractional penetration for a given particle diameter.
P_t	Fractional penetration summed over all diameters, = 1-E.
r_c	Eddy radius, ft.
s	Baffle spacing, ft.
t_c	Time for eddy to rotate 270°, sec.
$\bar{u}$	Average linear velocity, ft/sec.
u_r	Radial velocity of particle, ft/sec.
u_o	Terminal settling velocity of particle, ft/sec.
u_t	Tangential velocity of eddy, ft/sec.
V_c	Volume of gas cleaned per unit time per eddy, ft^3/sec.
V_t	Total volumetric gas flow rate, ft^3/sec.
w	Baffle height, ft.
μ	Gas viscosity, lb/(ft)(sec).
ρ_s	Particle density, lb/ft^3.

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2. Roshko, Anatol. "Some Measurements of Flow in a Rectangular Cutout", NACA Report TN3488 (August 1955).

FIGURE 1
SCHEMATIC DIAGRAM OF THE EXPERIMENTAL APPARATUS

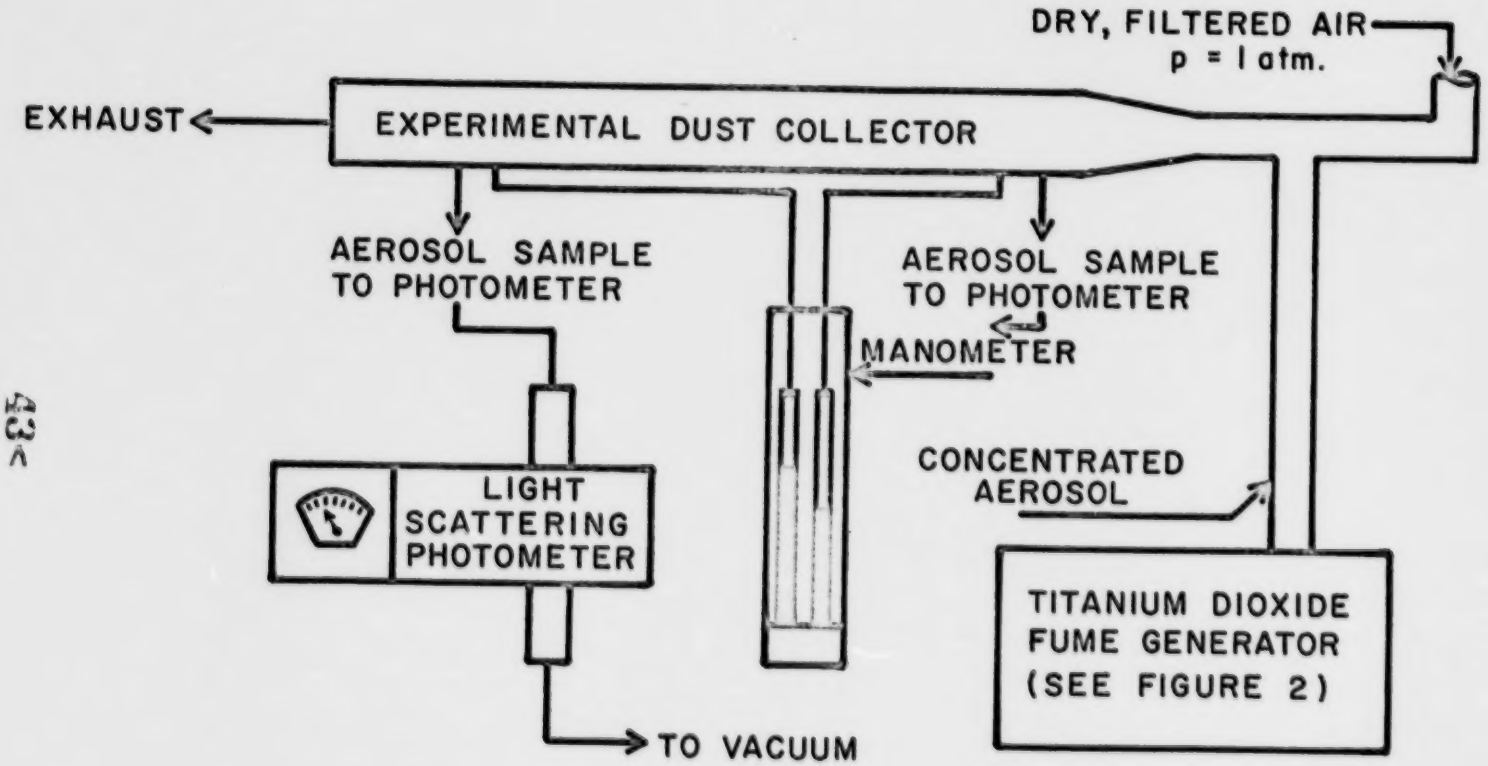


FIGURE 2
TITANIUM DIOXIDE FUME GENERATOR

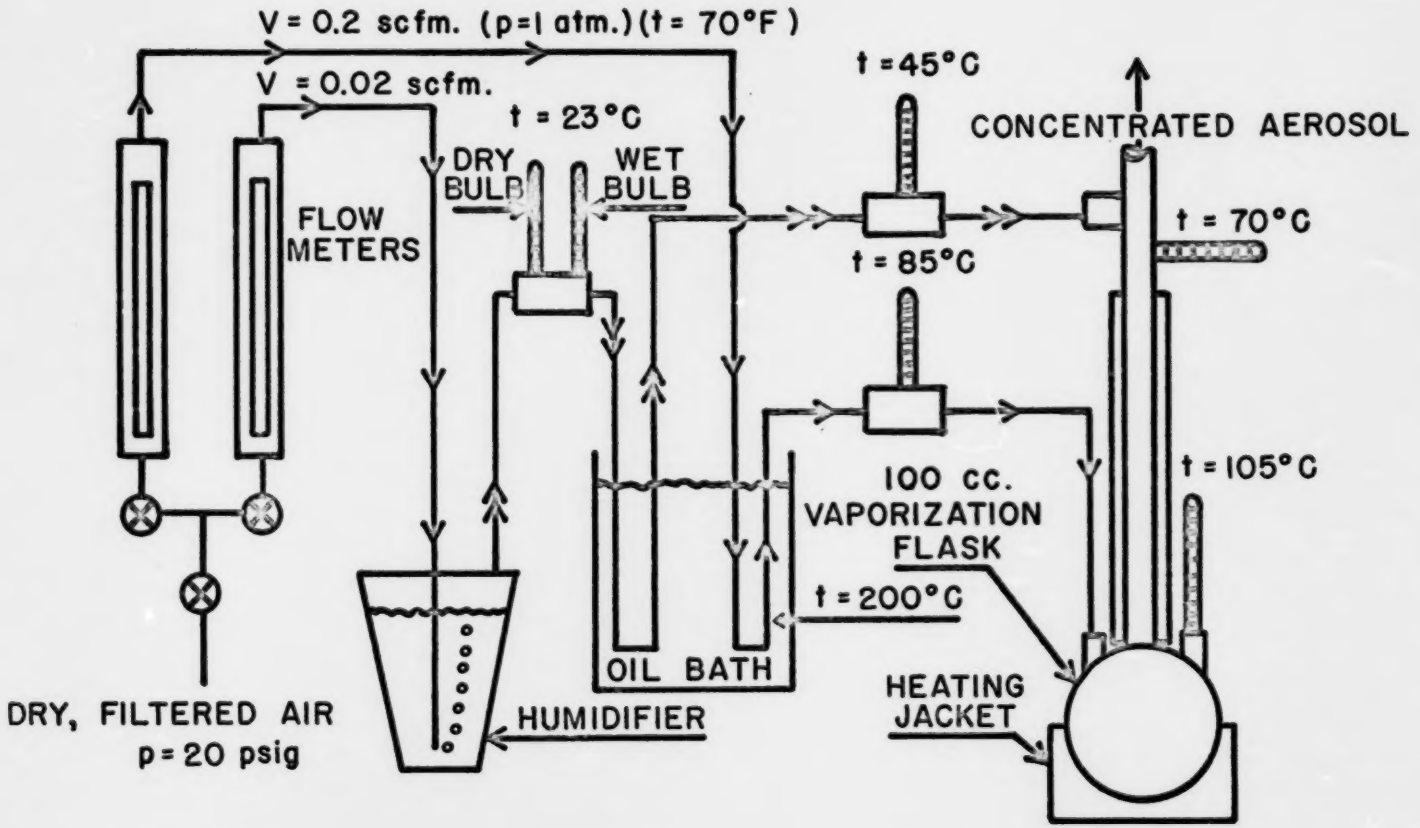


FIGURE 3
LIGHT SCATTERING PHOTOMETER

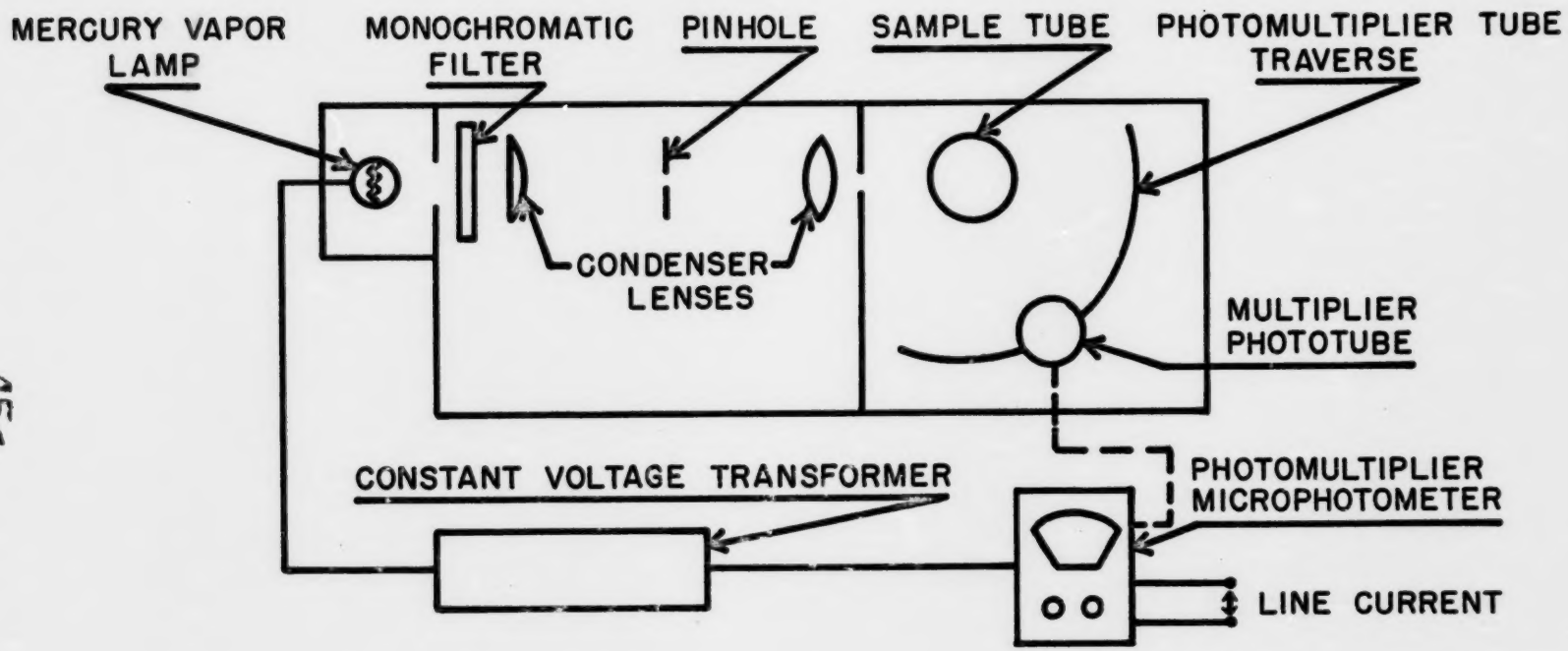


FIGURE 4
THE EXPERIMENTAL COLLECTOR

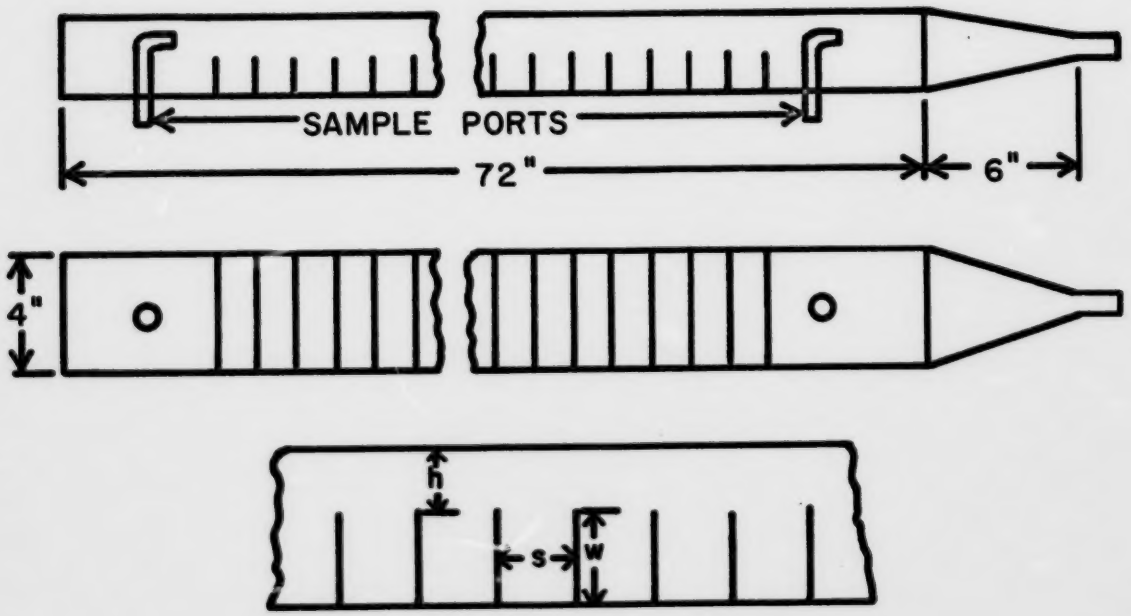


FIGURE 5

OVERALL COLLECTION EFFICIENCY VS. AVERAGE LINEAR VELOCITY

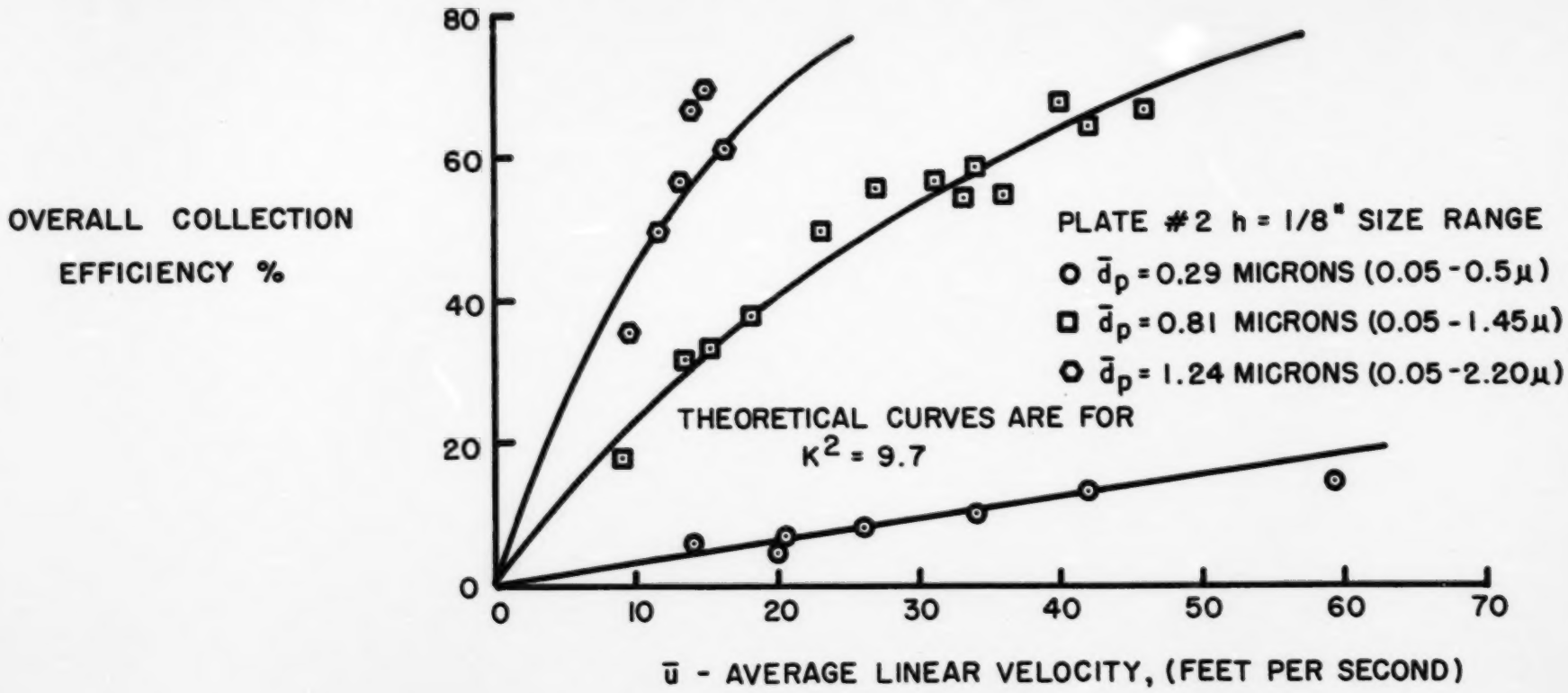


FIGURE 6
PRESSURE DROP VS. LINEAR AIR VELOCITY
FOR PLATE #2 WITH "h" AS PARAMETER

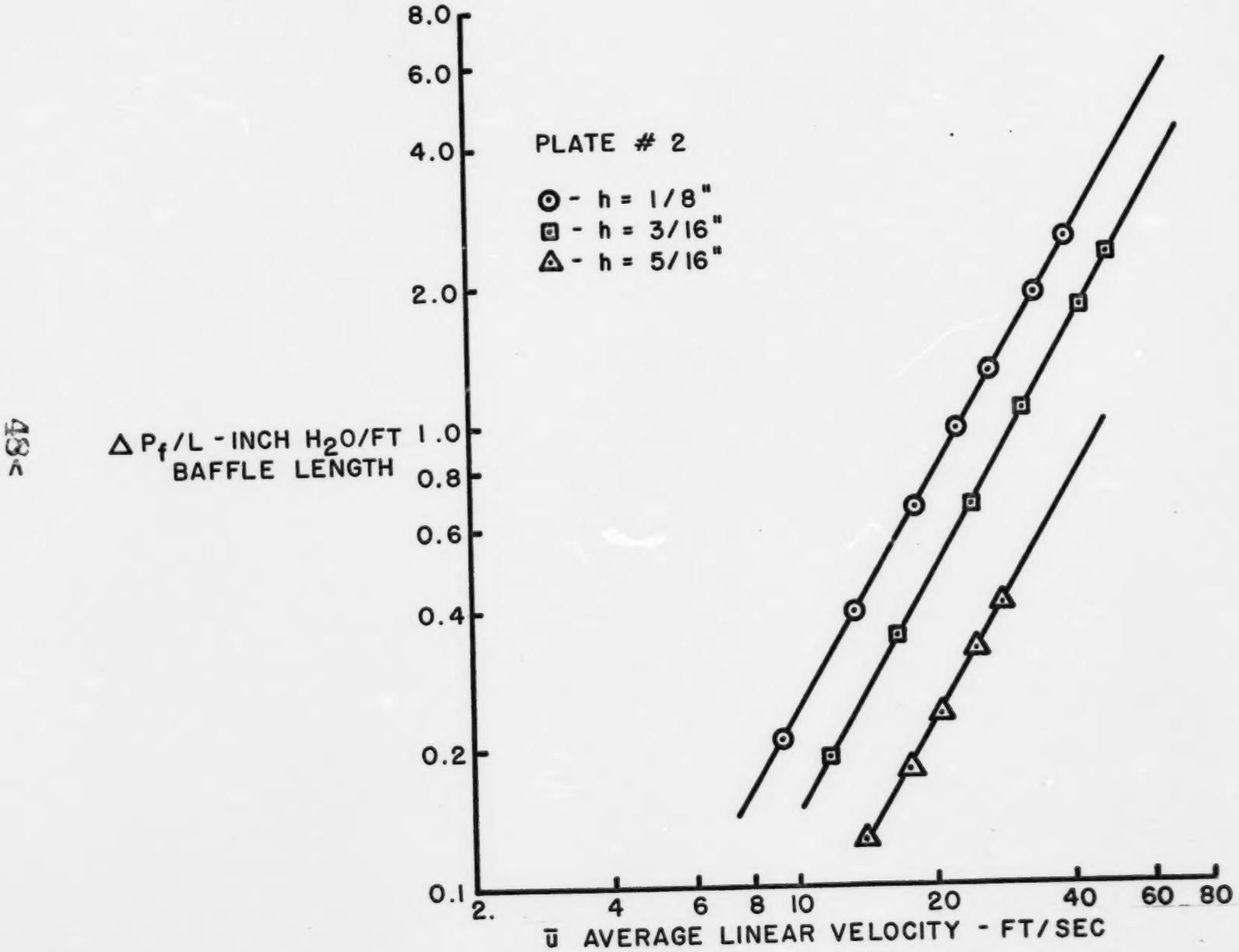


FIGURE 7
AREA UNDERSIZE VS. PARTICLE DIAMETER

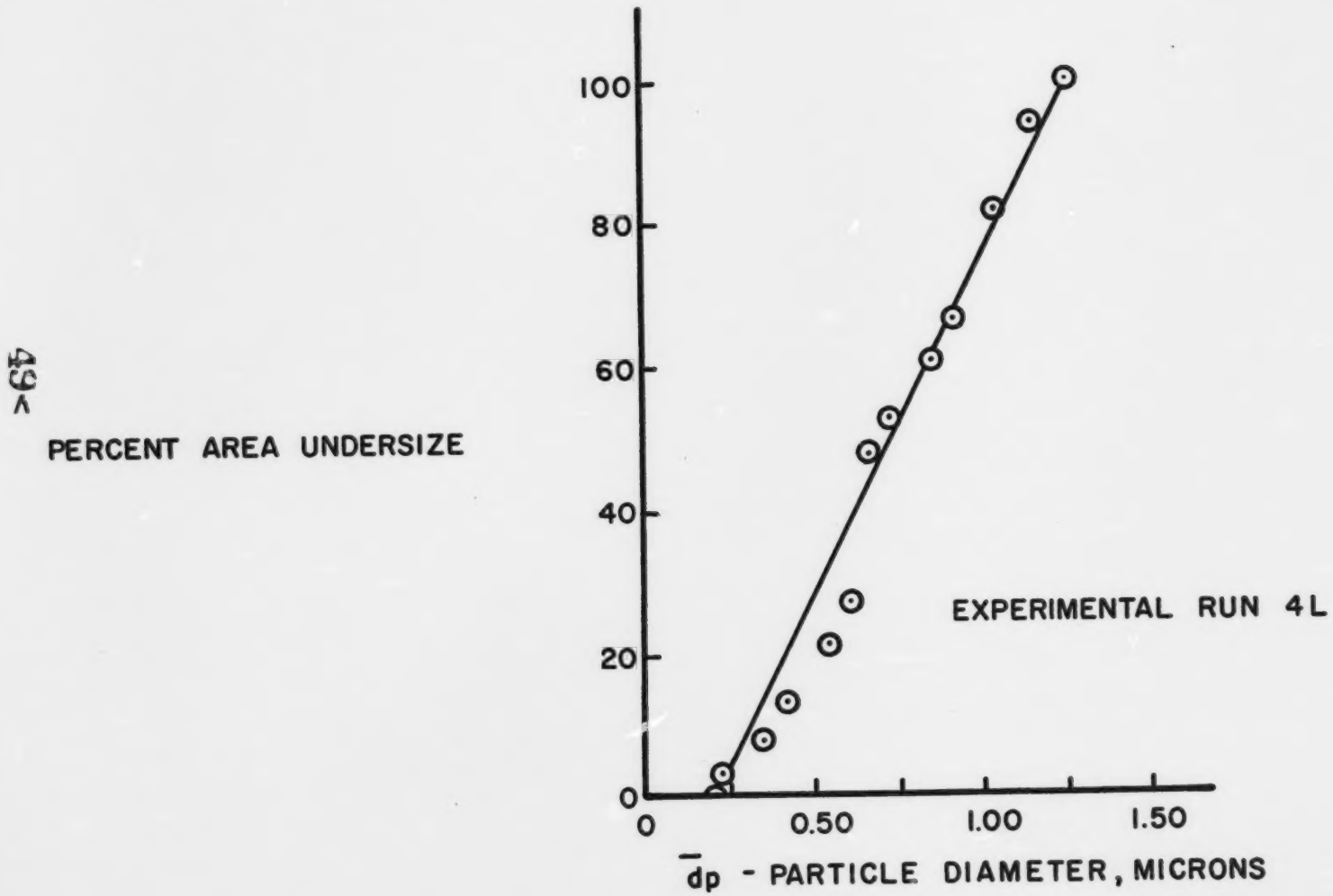
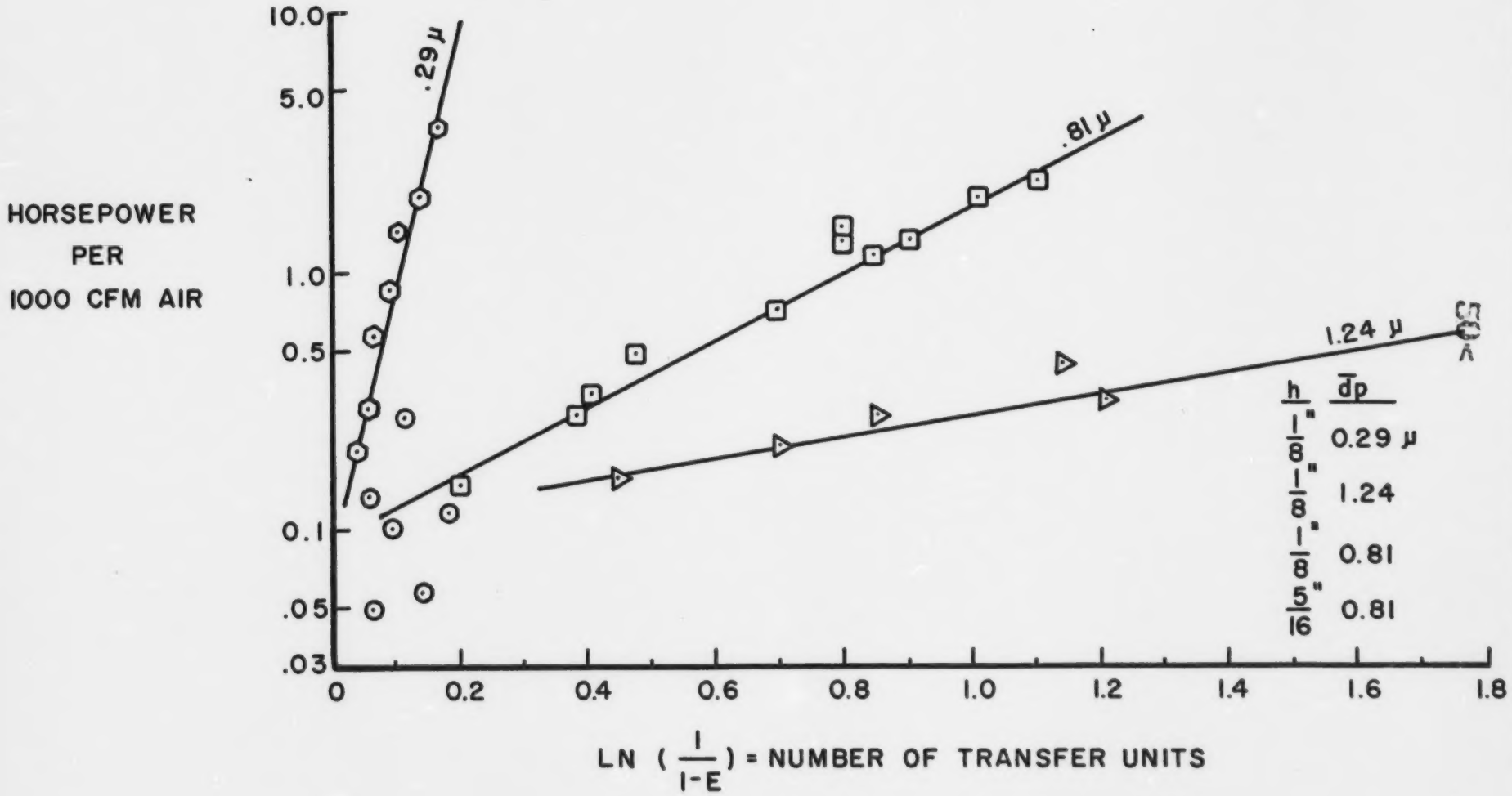


FIGURE 8

LN $(\frac{1}{1-E})$ VS LN (HORSEPOWER PER 1000 CFM AIR) WITH h AND $\overline{dp}$ AS PARAMETERS



APPENDIX E

Interim Progress Report on

MASS TRANSFER IN SECONDARY FLOW SYSTEMS

Thomas Sweeney

Introduction

The objective of the present work is the investigation of flow past transverse fins as applied to mass transfer. The effect of the fin height to spacing ratio on the mass transfer rate is of particular interest. This ratio, from the work of previous investigators, appears to determine the stability of the flow configuration between the fins.

A preliminary calculation of the expected liquid phase coefficient was performed based upon the following assumptions:

1. The penetration theory is valid (7) and (8).
2. A continuous liquid film forms over the fins.
3. The film thickness is the same as that of a film falling down a flat vertical plate.
4. The film is disturbed and completely mixed at three places in each fin unit.

Liquid phase coefficients are predicted to be of the same order of magnitude as those obtained in a packed tower.

Gas phase coefficients can be obtained by extending the heat transfer data of Boelter et al. (2). Very high coefficients are predicted.

Efficiencies of mass transfer will be determined for an apparatus in which a liquid flows down over fins while a gas flows upward. For any given transport system (of liquid, gas, and transferring components) the independent variables of interest are:

1. Gas flow rate
2. Liquid flow rate
3. Spacing of the fins
4. Height of the fins
5. The angle of inclination of the apparatus
6. The shape and type of fins

The apparatus described constitutes an absorption column. Data regarding other types of absorption columns are abundant. Thus it will be possible to compare the measured mass transfer rates with those obtained in a variety of equipment.

Systems

The transfer of a substance from one phase to another, such as ammonia from air to water, takes place through resistances in each phase. Any resistance due to the interface is usually assumed to be

zero. The performance of a gas absorber is influenced by the values of the liquid and gas phase resistances. It is useful to isolate the effects of liquid and gas phase resistances. This is done by using a gas which is slightly soluble to eliminate the effect of gas phase resistance and by using a highly soluble gas to eliminate the liquid phase resistance.

The liquid phase resistance will be studied by desorbing oxygen from water. The gas phase resistance will be studied by absorbing ammonia in water.

The oxygen will be determined in water by the Pomeroy-Kirschman-Alsterberg modification of the Winkler method (9). The oxygen content of the air will remain relatively constant through the column and need not be analyzed.

The ammonia will be determined in water by back titration of the acidified sample. The gas will be analyzed in a similar manner.

Equipment

A column has been constructed and preliminarily tested. The column consisted of a rectangular duct with windows. Plates with fins affixed can be inserted and bolted in place. This column has not been satisfactorily operated for two reasons. First, the falling liquid has a tendency to flow between the finned plates and the duct walls to which they are attached. Construction methods did not permit a tight fit. Second, the clearances between the fins and the duct sides are too large. The clearances cannot be made smaller in this equipment due to construction methods.

An improved column has been built and is being tested. This column is designed to eliminate the observed defects in the first column.

The experimental absorption apparatus consists of a rectangular duct constructed of two wide aluminum sides and two narrow plexiglass sides. Fins are affixed perpendicular to the aluminum plates transverse to the axis of the duct. Spacing between both baffle plates and baffles are changeable.

Air is introduced into an enlarged chamber at the column bottom. Liquid is introduced at the top of the column. Necessary heat exchangers, rotameters, et cetera are provided as shown in the sketch. Either oxygen or ammonia, depending on the experiment, is added to the system in an appropriate place.

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ESTIMATION OF EFFICIENCY FOR BUBBLER-TYPE GAS ABSORBERS

SEYMOUR CALVERT and WALTER WORKMAN
Department of Chemistry and Chemical Engineering,
Case Institute of Technology, Cleveland, 6, Ohio, U.S.A.

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Summary—The behaviour of bubbler-type absorbers is discussed, and used to predict an estimate of absorption efficiency for such absorbers and to indicate the factors which have the greatest effect on efficiency.

GAS analysis methods involving the selective collection of one or more components of a gaseous mixture in a liquid absorbent are subject to error if the absorption efficiency is unknown and may even be limited in feasibility if the efficiency is too low. It is important to be able to predict (or estimate) the efficiency of an absorption system and to control the factors which significantly affect efficiency. While performance data for laboratory-scale absorbers have been reported in the literature, they are not universally applicable and must be interpreted for any situation which is not identical with the original experiment.

The purpose of this paper is to present sufficient generalised information to serve as a basis for predicting the performance and understanding the behavior of bubbler-type absorbers. Bubblers were chosen for discussion because they are the simplest and most commonly used class of absorbers. Much of the general discussion which follows applies to all absorbers, but the design equations were developed for specific application to the case of bubbles rising through liquid.

An extensive general discussion of analytical absorbers is given by Jacobs[1] and performance data (also presented by Jacobs) are given[2] in the American Public Health Association Yearbook, 1939–40. It will be assumed here that these or other sources may be consulted for details of absorber construction and operating procedure. While there are many variations in design, bubbler-type absorbers generally involve the dispersion of gas into the bottom of a reservoir of liquid and withdrawal of the gas above the level of the "aerated" column of liquid.

Dispersion of the gas is obtained either by introduction of a gas jet from a submerged orifice or by introduction of gas through a sintered-glass plate or similar porous medium. Effective gas bubble size is practically independent of orifice (or pore) size when the bubble population is high[3]. This observation is attributed to the coalescence of small bubbles in the vicinity of the dispersion plate. While the bubble diameters are statistically distributed, the distributions measured by Houghton *et al.*[3] are fairly narrow and the average diameters range from 0.35 to 0.45 cm over a wide range of gas velocity.

Because the extent of absorption depends on both the residence time of a bubble in the aerated column of liquid and the bubble velocity relative to the liquid, it is important to have information on these quantities. Fig. 1 is a plot of bubble (air)

1

residence time per centimetre of non-aerated liquid (water) depth above the gas entrance versus superficial gas velocity (cm^3/min per cm^2 of absorber cross-sectional area) with absorber diameter as a parameter. The curve for 80 mm diameter is from the data of Houghton on gas hold-up and that for 22 mm is from the author's data on hold-up in a midget impinger.

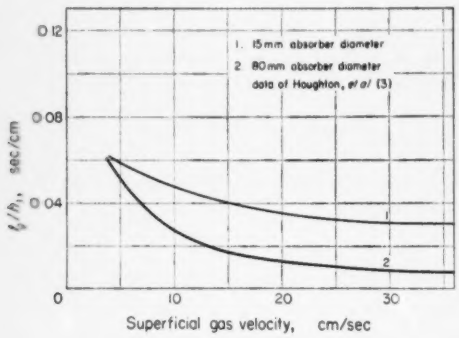

FIG. 1.

The residence time is practically independent of the method of gas dispersion so long as the superficial gas velocity is high enough to provide many bubbles. This would not be true for bubbles rising singly with a large distance between bubbles. It can be seen that so far as residence time and bubble diameter are concerned, there appears to be no value in using a fine fritted disc as compared with a coarse one. Although there is no information on the point, it would probably be unwise to use extremely large nozzles for dispersion. The midget impinger nozzle, for example, was about 1 mm, which would provide a gas jet velocity of 6,000 cm/sec at the point of maximum absorption efficiency.

The velocity of rise of single bubbles[4] is approximately constant at 24 cm/sec for diameters greater than 0.2 cm. While the average velocity relative to the absorber walls is lower than this where bubble population is high, we will approximate the velocity relative to the liquid as being equal to the velocity of rise of a single bubble.

DEFINITIONS OF SYMBOLS

A = Designation of transferring component.
a = Bubble radius, *cm*.
B = Designation of reactant in liquid.
C = Concentration of A in liquid, mol/cm^3.
C_a = Average concentration of A in liquid at any instant, mol/cm^3.
C_0 = Initial average concentration of A in liquid, mol/cm^3.
C_{Al} = Concentration of A in the liquid interface, mol/cm^3.
D = Diffusivity coefficient for A, cm^2/sec.
D_g = Gas phase diffusivity, cm^2/sec.
D_f = Fictitious gas phase diffusivity for cases of mixed resistance.
D_{T_1} = Diffusivity of A in water at T_1.
D_{T_2} = Diffusivity of A in water at T_2.

F = Overall instantaneous collection efficiency $= f\left(\frac{p_1 - HC_a}{p_1}\right) = f\left(\frac{p_1 - p_e}{p_1}\right)$.

f = Fractional instantaneous approach to equilibrium = $\frac{p_1 - p_2}{p_1 - HC_a}$ = equilibrium collection efficiency.

f_g = Equilibrium collection efficiency for gas phase controlling.
f_L = Equilibrium collection efficiency for liquid phase controlling.
f_L' = Equilibrium collection efficiency during period of movement of one bubble diameter relative to liquid.
G = Gas flow rate, cm^3/sec.
H = Henry's Law Constant, $\frac{atm}{mol/cm^3}$.
k_g = Mass transfer coefficient for gas phase, $mols/cm^2\text{-}sec\text{-}atm$.
k_{OG} = Overall gas-phase mass transfer coefficient based on driving force equal to average partial pressure of A in the gas minus the partial pressure in equilibrium with average liquid concentration, C_a.
k_L = Liquid-phase mass transfer coefficient, $mols/cm^2\text{-}sec\text{-}mol/cm^3$ based on driving force = $C_{A_i} - C_a$.
N = Diffusion rate, $mol/sec\text{-}cm^2$.
n = Total number of bubble diameters of relative motion during bubble residence time.
P = Total pressure, atm.
p_1 = Partial pressure of A in inlet gas, atm.
p_2 = Partial pressure of A in outlet gas, atm.
p_e = Partial pressure of A in equilibrium with liquid concentration, C_a, atm.
q = Concentration (average) of B in liquid for one mole of B reacting with one mole of A, mol/cm^3.
R = Gas law constant = 82.057, $\frac{atm\text{-}cm^3}{mol\text{-}^\circ K}$.
T = Absolute temperature, °K.
t_a = Total time of absorption, sec.
t_g = Residence time of a gas bubble, sec.
t_L = Time of exposure of fresh liquid surface to gas bubble.
u_b = Bubble velocity relative to liquid, cm/sec.
u_g = Superficial gas velocity, $cm^3/min\text{-}cm^2$.
V_L = Volume of liquid in absorber, cm^3.
x = Distance in direction of diffusion, cm.
π = 3.1416.
ρ_g' = Molar density of gas, mol/cm^3.
μ_{T_1} = Viscosity of water at T_1, $centipoises$.
μ_{T_2} = Viscosity of water at T_2.

Mass transfer

The fundamental process in an absorber involves the tendency toward equilibrium between the gas and the liquid in contact with it. This may involve the transfer of several components between the phases, but it will be assumed here that the liquid is non-volatile and that if there is more than one component in the gas phase, they may be considered independently. Thus we are concerned with the transfer of one component, A, from the gas to the liquid.

Because each bubble is in contact with the liquid for a limited time, equilibrium will not be attained and the degree of approach to equilibrium will be determined by the rate of transfer of A. Mass transfer rate in a bubbler can best be considered quantitatively in terms of unsteady-state diffusion rather than the "two-film" theory because of the generally small effects of turbulence in either fluid phase. However,

a simpler qualitative description can be given in terms of steady-state diffusion, where for a one-dimensional case:

$$N = -D\frac{\partial c}{\partial x}\ \frac{(\text{mols})}{(\text{sec–cm}^2)} \tag{1}$$

Equation (1) states that the rate of diffusion depends on the diffusivity and the concentration gradient, $\partial c/\partial x$.

Although, in general, the rate of mass transfer is determined by the concentration gradients and diffusivities of both phases, there are two limiting cases in which the rate is controlled by either the liquid or the gas phase. To illustrate, consider the purely physical absorption (*i.e.*, a reversible equilibrium process such as the solution of oxygen in water) of A from a bubble rising through a liquid. If A is extremely soluble in the liquid just at the interface, a low gas-phase concentration would be in equilibrium with a high liquid-phase concentration. Consequently, a high concentration gradient would exist between the liquid at the interface and the bulk of the liquid. Because the rate of diffusion from the gas must equal the rate of diffusion into the liquid, there must be a fixed ratio of gas concentration gradient to liquid concentration gradient. In order to maintain this ratio the interfacial gas concentration must be quite small and indeed, it approaches the concentration in equilibrium with the bulk of the liquid. In this limiting case the concentration gradient in the gas phase becomes practically identical with that which would exist if there were no liquid phase concentration gradient.

The other limiting case, liquid phase controlling, occurs when a gas of very low solubility is being absorbed. The maximum possible liquid-phase concentration gradient will be so small that the gas-phase concentration gradient must be small if the transfer rates in the two phases are to be equal. Here the liquid-phase concentration gradient may be approximated as that which would exist if there were no concentration gradient in the gas.

Gas phase controlling

The rate of mass transfer from a bubble, if gas-phase resistance controls, is represented in Fig. 2, a graph of fractional approach to equilibrium, f_g, versus a

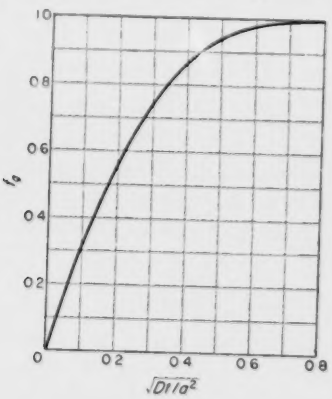

FIG. 2.

dimensionless time group, $\sqrt{Dt_g/a^2}$. This figure represents the solution of the equations for unsteady-state diffusion from a sphere which is initially at a uniform concentration and which is in contact with liquid of constant, uniform composition as given by Crank[5]. Physically, this corresponds to a bubble contacting liquid whose composition does not change appreciably during the period of contact (for this bubble) and under conditions such that gas-phase resistance is controlling.

One must distinguish between overall collection efficiency, F, which represents simply the fraction of A absorbed, and equilibrium collection efficiency, f, which represents the fractional absorption of that portion of A which would be absorbed if equilibrium were attained. It will be recognised that if the reaction products are such that there is an appreciable equilibrium vapour pressure above the liquid, the amount of A which can be removed from the gas will decrease as the concentration of the liquid increases. Thus, while the first bubbles of gas might transfer 99% of their A-content to fresh liquid (barren of A-reaction products), later bubbles might contact liquid so concentrated that they could not possibly transfer more than, say, 50% of the A-content even though they would still attain 99% of this equilibrium limit.

Liquid phase controlling

If liquid-phase resistance is controlling, the fractional approach to equilibrium is given by:

$$f_L' = \left(\frac{2D}{\pi a u_b}\right)^{1/2}\left(\frac{6RT}{H}\right) \tag{2}$$

and

$$(1 - f_L) = (1 - f_L')^n \tag{3}$$

These relationships were derived on the basis of Higbie's Penetration Theory, which states that the rate of diffusion from a sphere is given by the rate of diffusion into a semi-infinite medium which is originally at a uniform concentration, C_0, over a period of time, t_L, which may be approximated as the time required for the bubble to rise one diameter, $2a/u_b$. The fraction f_L' is equal to the change in concentration of the gas divided by the maximum change possible (for gas in equilibrium with liquid at C_0) which occurs during the time the bubble rises one diameter. The total fractional approach to equilibrium, f_L, is given for a bubble rising through n diameters, where n equals the number of diameters of relative movement per second, $u_b/2a$ times the residence time. The velocity relative to the liquid, u_b, may be taken as 24 cm/sec for this purpose and for bubble diameters of 3.5–4.5 mm.

Although the distinction between gas phase controlling and liquid phase controlling has been given above in comparative qualitative terms, it can now be given quantitatively. The basic relationship is based on the two-film concept of mass transfer, which is discussed in any text-book of chemical engineering, and describes the relationship between a mass transfer coefficient, k_g, based on the actual gradient in the gas phase (which requires that interfacial concentrations be known), and an overall coefficient, k_{OG}, based on the gradient for the assumption of gas-phase controlling (which requires knowledge of bulk concentrations only):

$$\frac{k_g}{k_{OG}} = 1 + H\frac{k_g}{k_L} \tag{4}$$

If the ratio, k_g/k_{OG}, is unity, then the gas phase controls. Liquid-phase resistance is important if the ratio is significantly greater than one and may be said to control if the ratio is greater than 10. We may evaluate the ratio by using the following expressions for gas-phase coefficient, k_g, and liquid-phase coefficient, k_L. The expression for k_g is an approximate representation of the relationship given in Fig. 2 and the expression for k_L results from penetration theory.

$$k_g = \frac{7.6(D_g)^{0.7}}{3RT(t_g)^{0.3}(a)^{0.4}} \tag{5}$$

$$k_L = 2\sqrt{\frac{D_L u_b}{2\pi a}} \tag{6}$$

We can estimate the ratio k_g/k_L for average conditions where a gas is being absorbed from air into an aqueous solution at room temperature. The bubble radius, a, is taken as 0.2 cm and the velocity of rise, u_b, as 24 cm/sec. Representative diffusivities are gas diffusivity, $D_g = 0.1$ cm²/sec and liquid diffusivity $= 1.5 \times 10^{-5}$ cm²/sec. Upon making the substitutions it is seen that $k_g/k_L = 1.87 \times 10^{-3}$ for "average" conditions. Thus we may say that gas-phase resistance controls [*i.e.* $-(k_g/k_{OG}) < 1.1$] if H is less than 54 $\frac{\text{(atm)}}{\text{(mol/cm}^3\text{)}}$ and that liquid phase controls [$(k_g/k_{OG}) > 10$] if H is greater than 4,800 $\frac{\text{(atm)}}{\text{(mol/cc)}}$.

Intermediate cases may be approximated by considering the absorption to be gas-phase controlled and by using a fictitious diffusivity, D_f, such that:

$$\frac{k_g}{k_{OG}} = \left(\frac{D_g}{D_f}\right)^{0.7} \tag{7}$$

or

$$D_f = D_g \left(\frac{k_{OG}}{k_g}\right)^{1.43}$$

Chemically reactive solutions

Examples of the prediction of absorption efficiencies for each of the three cases discussed above are given later in this paper. Before turning to them we must consider two more matters of general importance. The first of these is the consideration of absorption by a chemically reactive solution, which probably includes the majority of applications in gas analysis. In the ideal situation one might picture the liquid-phase reaction as being extremely rapid and the reaction products such that the vapour pressure of A in equilibrium with the liquid interface is negligible. Where this is approximately true, the absorption is gas-phase controlled, and the absorption will be substantially complete in the contact time attained in most laboratory absorbers.

Even though the reaction products might be non-volatile, however, there is still no assurance that liquid-phase resistance will be negligible. It is necessary that the reacting substance, B, diffuses through the liquid towards the interface and reacts at a high enough rate to match the rate of diffusion of A into the liquid. If B diffuses

too slowly or if the reaction is too slow, the reaction zone may be displaced a considerable distance into the liquid with the result that the equilibrium pressure of A above the liquid interface will rise.

The magnitude of the effect of reactant diffusion rate is illustrated mathematically in the solution[6] for the case wherein the second order reaction between A and B, yielding a non-volatile product, is infinitely rapid and the diffusivities of A and B are equal:

$$k_L = \left(1 + \frac{q}{C_{Ai}}\right) 2\sqrt{\frac{D_L u_b}{2\pi a}} \tag{8}$$

It can be seen that if the ratio of the average concentration of B to the concentration of A at the liquid interface, q/C_{Ai} is small, the liquid-phase transfer coefficient, k_L, is the same as that for physical absorption. This bears out the qualitative observation that the concentration of B must be high relative to the concentration of A in order for liquid-phase resistance to be substantially eliminated. If the absorption can be described as liquid-phase controlled at zero concentration of B, then the effect of B on the fractional approach to equilibrium per bubble diameter of rise is given by:

$$f_L' = \left(1 + \frac{q}{C_{Ai}}\right)\left(\frac{2D}{\pi a u_b}\right)^{1/2}\left(\frac{6RT}{H}\right) \tag{9}$$

If the absorption is to be considered as overall gas-phase controlled, then the ratio k_g/k_L in equation (4) should be divided by $[1 + (q/C_{Ai})]$.

Liquid flow pattern

The final matter of general importance is the effect of liquid flow pattern in the absorber. In the previous discussion it has been assumed that the liquid is completely mixed so that the liquid composition encountered by any one bubble at the bottom of the absorber is the same as that encountered at the top by the same bubble. In other words, the rate of change of liquid-phase composition was assumed small with respect to the residence time of any one bubble because the amount of liquid associated with the bubble is large.

It is possible to have a definite circulatory liquid flow pattern set up so that some small fraction of the liquid travels up with a bubble and experiences little mixing with the bulk of the liquid during its upward travel. The result will be that the liquid contacting the bubble at the top of the absorber is more concentrated in A than the bulk of the liquid. Where the absorption process is purely physical, the minimum concentration of A in the gas leaving the absorber will be limited to that in equilibrium with the liquid last contacting the bubble. In the case of absorption with a reactive solution there may be no adverse effect if the concentration of the reactant is not appreciably depleted.

While it is not now possible to quantitatively characterise the co-current movement of liquid with the gas, evidence of its existence has been observed. The discussion of the absorption of ammonia in water, given later, points out the probable effect of co-current flow at low gas flow rates. Study of the absorption of carbon dioxide in water in an absorber in which the bubbles travel up in a helical path formed in a glass liner is at present being conducted by the authors and has shown that there is pronounced co-current flow in this apparatus.

Where co-current flow does exist in physical absorption, it can be shown mathematically that, for the same residence time, the approach to equilibrium, f, will be greater than for the case of complete mixing of the liquid phase. However, the shifting of the equilibrium limit will more than compensate for the increase of f in causing overall collection efficiency, F, to decrease.

EXAMPLES

Some examples of gas absorption in bubblers for which experimental data are available will now be considered in order to illustrate both the application of the design principles and the order of accuracy which can be attained. It must be emphasised that the predicted efficiencies can only be interpreted as approximations and that for precise work the efficiency must be determined for the particular system.

Liquid phase controlling

The absorption of carbon dioxide by aqueous solutions of sodium hydroxide, sodium carbonate and ammonia in nozzle-type bubblers has been reported by Mochalova and Kishinevskii[7]. Their data for absorption in pure water (extrapolated to 0% Na_2CO_3) will be compared with predictions based on liquid-phase resistance controlling. The apparatus used consisted of a 0.5-cm diameter tube pointed downward with the end of the tube submerged 1.7 cm below the liquid level in a 5-cm diameter cylinder. Measured absorption efficiencies were 7.61% at 5°C and 7.39% at 45°C. The total gas rate was cited as 0.6 litres per minute (we assume this to be at standard conditions), which corresponds to a superficial gas velocity of 0.51 (cm/sec).

Solubility data[8] were converted to values of H equal to $1.57 \times 10^4 \left(\frac{\text{atm}}{\text{mol/cm}^3}\right)$ at 5° and $4.57 \times 10^4 \left(\frac{\text{atm}}{\text{mol/cm}^3}\right)$ at 45°. Applying the criterion of equation (4) indicates that liquid phase controls, since H is greater than 4.8×10^3. Thus the absorption efficiency should be predicted with equations (2) and (3). Diffusivities for carbon dioxide in water of 1.14×10^{-5} (cm²/sec) at 5°C and 3.19×10^{-5} (cm²/sec) at 45°C were estimated from the International Critical Tables value of 1.8×10^{-5} (cm²/sec) at 20°C by means of the following relationship[9] for dilute aqueous solutions:

$$D_{T_1} = D_{T_2} \left(\frac{\mu_{T_2}}{\mu_{T_1}}\right) \tag{10}$$

The viscosities μ_{T_2} and μ_{T_1} are those of water at the temperatures T_2 and T_1. If the liquid viscosity is much different from that of water, equation (10) will not apply and another relationship[9] must be used.

Because the orifice size is relatively large (5 mm) and the gas rate is low, we would expect that the bubbles would emerge singly as reported. Thus, the velocity of rise, u_b would be about 24 (cm/sec) for an assumed bubble radius, a, of 0.2 cm. Substitution of these values into equation (2) leads to values for f_L' of 0.0107 at 5° and 0.007 at 45°. At the low superficial gas velocity used there is no significant difference between aerated and non-aerated liquid heights, so the value of n is 4.25 bubble diameters for a submergence of 1.7 cm.

The efficiencies, f_L, are then computed to be 4.5% at 5°C and 3.0% at 45°C. If

we take into account the fact that, because the orifice is pointed downward the bubble path will be a curve rather than a straight line, we might reasonably expect (as confirmed by observation) the path to be a few bubble diameters longer. If n is taken as 7.0, the values of f_L will be 7.3% at 5°C and 4.8% at 45°C. This approximation to the experimental values of 7.61% and 7.39% is about as good as can be expected considering all of the estimations involved in the calculations and the extremely small contact time.

Chemical reaction and gas phase controlling

Air contaminant absorption efficiencies for several models of bubblers have been determined by Roberts and McKee[10]. Collection of sulphur dioxide in disodium tetrachloromercurate and of chlorine in 0.1N sodium hydroxide were reported as "... substantially complete regardless of the type of sampler or the flow rate used ...". For the absorption of 1 ppm (by volume) of ammonia from air in distilled water the efficiencies were lower and were dependent on air flow rate (see Fig. 3).

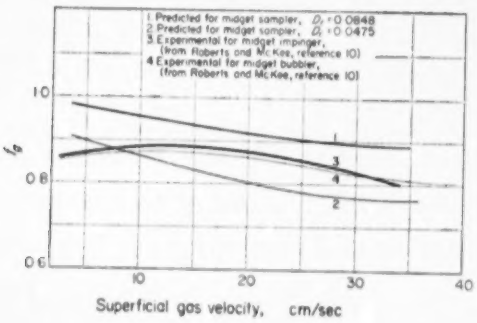
1. Predicted for midget sampler, Δ, = 0.0848
2. Predicted for midget sampler, Δ, = 0.0475
3. Experimental for midget impinger, (from Roberts and McKee, reference 10)
4. Experimental for midget bubbler, (from Roberts and McKee, reference 10)
1.0
0.8
0.6
10
20
30
40
Superficial gas velocity, cm/sec

FIG. 3.

If we assume that the concentrations of sulphur dioxide and chlorine (data were not given) were of the same order as that of ammonia,* we may consider these two cases as being gas-phase controlled because the ratio (q/C_{Ai}) would be very high. Considering the case of chlorine absorption, for example, we find a value of $H = 1.33 \times 10^4 \left(\frac{\text{atm}}{\text{mols/cm}^3}\right)$ for un-ionised chlorine solubility[6] and approximately half that for total chlorine solubility. Employing the criterion of equation (4), this value of H indicates liquid-phase controlling if there is no chemical reaction. The effect of chemical reaction (assuming a second order, rapid reaction) can be estimated by means of equation (8) if we assume that C_{Ai} is in equilibrium with a gas-phase interface with chlorine concentration of 1 ppm ($p_1 = 1 \times 10^{-6}$ atm). Computation yields $C_{Ai} = 0.75 \times 10^{-10}$ mols/cm^3 and we have $q = 1 \times 10^{-4}$ equiv./cm^3. Putting C_{Ai} in terms of equivalents, since one mole of chlorine reacts with two equivalents of sodium hydroxide, we compute $q/C_{Ai} = 0.67 \times 10^6$.

For purposes of estimation we take $k_g/k_L = 1.65 \times 10^{-3}$ for the case of no reaction and obtain $k_g/k_L = 2.46 \times 10^{-9}$ for this case of chemical reaction. The group $H(k_g/k_L)$ can now be computed to be 3.3×10^{-5} and substitution in equation (8)

* Communication with Dr. McKee verified this assumption.

indicates that this is a case of gas-phase resistance controlling. One notes that, since gas phase is controlling, the concentration gradient in the gas would cause the partial pressure of chlorine at the interface, and consequently C_{Ai}, to be lower than that assumed (the average partial pressure, p_1), and thus the ratio, q/C_{Ai}, would be larger. It can be seen, then, that to base the computation on C_{Ai}, as given by the maximum gas-phase composition, will yield a conservative result.

The next step is to compute fractional approach to equilibrium based on gas-phase controlling. Diffusivities in air at 20°C were computed from values at 0°C by the method recommended in Reid and Sherwood[9] as 0.14 cm²/sec for sulphur dioxide, 0.143 cm²/sec for chlorine and 0.228 cm²/sec for ammonia. Assuming a bubble radius of 0.2 cm, a liquid volume of 10 cm³,* and a bubbler cross-sectional area of 3.6 cm² (for a standard Midget Impinger), we compute the un-aerated liquid height to be 2.78 cm and can proceed to find residence time and f_g. At a superficial gas velocity of 15 cm/sec, Fig. 1 indicates a residence time of 0.04 seconds per centimetre of un-aerated height or 0.11 sec for 2.78 cm of liquid. By use of Fig. 2 the efficiencies are computed to be 0.984 for sulphur dioxide and chlorine, and 0.998 for ammonia.

Resistance in both phases

These predictions of f_g may be assumed to be equivalent to F if the testing time was so short that the liquid concentration did not rise appreciably. The predictions for sulphur dioxide and chlorine bear out the statement[10] that absorption was substantially complete. The prediction for ammonia is far from agreement with the experimental results shown in Fig. 3, in spite of the fact that $H = 13.5 \frac{\text{atm}}{\text{mol/cm}^3}$ (for dilute solutions[6]), and one would expect gas phase to be controlling from the criterion of equation (4).

We find that this same characteristic of ammonia absorption in water has been observed in large, industrial equipment[6] and that ratios of k_g/k_{OG} ranging from 2 to 3 have been determined experimentally. The existence of this additional resistance has been attributed to the possibility of a slow reaction between dissolved ammonia and ionised ammonia. There is also the possibility that the rate of accommodation at the interface is low. If we employ the extremes of the ratio, as given above, the corresponding values for D_f are 2.69 and 4.8 (see equation (7)). The predicted curves of efficiency versus flow rate are shown in Fig. 3.

While it is clear that the prediction covers too large a range of efficiencies to be useful in precise work, the "bracketing" of the experimental values at higher velocities is good confirmation of the mechanistic approach. The deviation of the slopes at low gas velocities is believed, by us, to be largely due to co-current flow, and to some extent to inaccuracy of bubble residence times as computed from gas hold-up. A definite circulatory liquid flow pattern can be observed at low gas flow rates and we believe that this results in a significant increase of ammonia concentration in the small volume of liquid which accompanies the bubbles.

CONCLUSIONS

The design methods presented above may be used to predict an estimate of absorption efficiency for a bubbler-type absorber and to point out which factors have the

* Communication with Dr. McKee verified this assumption.

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most important effect on efficiency. A recommended procedure for predicting efficiency is given below. It should be emphasised that this procedure is based on conservative approximations. High values for both bubble diameter and bubble velocity are used and the beneficial effect of circulation within bubbles is neglected. The approximate method for treating cases of mixed resistance is presented because of its simplicity although a rigorous solution for this case is given by Crank[5]. In any case, the prediction cannot be relied on for precise results and the specific system must be calibrated experimentally.

Recommended procedure

I. Determine whether the system is gas- or liquid-phase controlled or intermediate by means of the criterion of equation (4). For high concentration, either an average value of H may have to be estimated or the absorption process may have to be considered over incremental ranges of concentration in which H is approximately constant.

II. If the system involves purely physical absorption, evaluate the fractional approach to equilibrium by means of Fig. 2 for gas-phase controlling and equations (2) and (3) for liquid-phase controlling. For intermediate resistance use the relationship of Fig. 2 with a fictitious diffusivity given by equations (4) and (7). The ratio of k_g/k_L may be either estimated as the "average" value of 1.86×10^{-3} or it may be computed by means of equations (5) and (6).

If the absorption is to be carried on for a long time so that the liquid concentration builds up enough to impose an equilibrium limit on efficiency, the total amount of collection can be determined by integrating the relationship between the instantaneous rate of increase of liquid concentration and the liquid concentration. For an initial liquid phase concentration of zero and constant inlet gas concentration, the result is:

$$\ln\left(1 - \frac{HC_a}{p_1}\right) = -f\left(\frac{HG\,p_g'}{V_L P}\right) t_a \tag{11}$$

III. If the system involves chemical reaction in the liquid phase and there is negligible equilibrium pressure of the transferring component above the reaction products, the maximum collection efficiency corresponds to the case of gas-phase controlling. The effect of reactant concentration for a second order reaction may be estimated by dividing k_g/k_L in equation (4) by $(1 + (q/C_{Ai}))$. Other reaction mechanisms are discussed by Crank.[5]

In cases where an appreciable equilibrium pressure results from the reaction, the overall collection efficiency must be computed from the fractional approach to equilibrium as in the case of physical absorption.

IV. Having used the methods described above to design an appropriate absorption system, the performance of the system should be determined experimentally. The preferable method is to sample a gas mixture of known composition. If this is not possible, use two or more absorbers in series.

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Zusammenfassung—Die Eigenschaften von Absorber des Gasblasentyps werden diskutiert. Es wird versucht auf Grund der Eigenschaften vorauszusagen wie gross die Absorptionsfähigkeit solcher Absorber ist und die Faktoren herauszuarbeiten, die den grössten Einfluss auf die Leistungsfähigkeit haben.

Résumé—Les auteurs discutent le comportement d'absorbeurs du type barboteur et utilisent les résultats obtenus pour prévoir une estimation du pouvoir d'absorption de tels absorbeurs et pour indiquer les facteurs qui influent le plus sur ce pouvoir d'absorption.

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Appendix G

The Efficiency of Small Gas Absorbers

By

Seymour Calvert and Walter Workman

The first step in many gas analysis procedures is the collection of a gaseous pollutant from an air sample by means of a small absorber filled with an absorbing liquid. There must be some assurance that the absorption efficiency is accountable if the subsequent analytical result is to be viewed with confidence. Although the literature provides some information on specific cases, it is very desirable to have a general approach which will permit interpretation of reported results as well as providing principles for the design of new absorption systems.

A variety of absorber designs have been reported (ref. 1 and 2) and many more are conceivable yet it is possible to deal with the majority of them in a general fashion. The simplest and most widely used absorbers involve the bubbling of the gas sample through a fixed quantity of liquid and it is this type which will be discussed here. Our objective is to present methods for predicting absorber efficiency which will be convenient and simple to use. Because of this, most of the final presentations are based on some simplifying assumptions which will be clearly stated.

As will be seen, the importance of these simplifications is minor when compared with factors dependent on the chemical nature of the system. The most desirable type of system involves a liquid constituent which reacts with the pollutant to yield a non-volatile product. The other major type involves a reversible physical absorption which results in a solution with appreciable pollutant vapor pressure. High efficiency will generally result when a sufficiently strong chemically reactive solution is used. Low efficiency will be obtained for physical absorption unless the pollutant is very soluble and the ratio of gas to liquid volume is small.

For these extremes the design of the absorber and its intrinsic efficiency are of secondary importance. In order to handle the complete range of possibilities, however, we must be able to predict:

1. The intrinsic efficiency or fractional approach to equilibrium (f) for any one bubble passing through the absorber.

2. The average efficiency (F_A) for the entire gas sample.

FACTORS INVOLVED IN INTRINSIC EFFICIENCY

Bubbles in contact with the liquid will tend toward equilibrium with the liquid at a finite rate. After a sufficiently long time of contact equilibrium is reached and a definite mass of pollutant would have transferred from the gas to the liquid. In a short time of contact only a fraction, f, of this maximum mass would be transferred. In order to predict the amount of transfer we must first have some information regarding the physical behavior of bubbles dispersed in liquids.

Dispersion of the gas is accomplished either by introduction of a gas jet from a submerged orifice or by introduction of gas through a sintered glass plate or similar porous medium. Effective gas bubble size is practically independent of orifice (or pore) size when the bubble population is high. This observation is attributed to the coalescence of small bubbles in the vicinity of the dispersion plate. While the bubble diameters are statistically distributed, the distributions measured by Houghton et al., (3) are fairly narrow and the average diameters range from 0.35 to 0.45 cm. over a wide range of gas velocities. It can be seen that so far as bubble diameters are concerned there appears to be no value in using a fine fritted disc as compared with a coarse one. Although there is little information on the point, it would probably be unwise to use extremely large nozzles for dispersion. The midget impinger nozzle, for example, is about 1 mm., which provides a gas jet velocity of 6,000 cm/sec at the point of maximum absorption efficiency.

Because the extent of absorption depends on both the residence time of a bubble in the aerated column of liquid and the bubble velocity relative to the liquid, it is important to have information on these quantities. Figure 1 is a plot of bubble (air) residence time per centimeter of non-aerated liquid (water) depth above the gas entrance (t_g/h_1) versus superficial gas velocity (U_g-cm^3/sec per cm of absorber cross-sectional area) for typical commercial absorbers.

It is noted that the quantity t_g/h_1 is sensitive to several parameters:

1) Tube diameter - this is especially true for small tubes (less than 25 mm.).

2) h_1, the original height of liquid.

3) The particular dispersion method used. This latter effect is probably due in a large measure to end effects near the gas entrance.

For any given absorber one can easily determine the quantity t_g/h_1 by experimental measurement. It is first necessary to note the height of unaerated liquid about the gas entrance, then measure the height of aerated liquid

at the desired rate of bubbling. The quantity t_g/h_1 can then be calculated from:

$$t_g/h_1 = \frac{1 - h_1/h_2}{(h_1/h_2)\, U_g}$$

The velocity of rinse of single bubbles (4) is roughly constant at 24 cm/sec for bubble diameters greater than 0.2 cm. While the average velocity relative to the absorber walls is lower than this where bubble poplulation is high, we will approximate the velocity relative to the liquid as being equal to the velocity of rise of a single bubble.

Transfer From Bubbles

We may set a lower limit for the rate of mass transfer from bubbles to the gas-liquid interface by considering the process to involve only molecular diffusion from a stagnant sphere even though gas circulation within the bubble would increase the rate. The transfer rate from the interface into the liquid is given fairly well by Higbie's penetration theory as:

$$k_L = \sqrt{\frac{2D_L\, u_B}{\pi a}}$$

The time of contact or surface renewal is taken as $\left(\frac{2a}{u_B}\right)$, the required for a bubble to rise through one diameter of height.

If it is assumed that each bubble contacts liquid of constant average composition during its entire period of rise, we may use the solution given by Crank (5)

$$f = 1 - \sum_{n=1}^{\infty} \frac{6L^2\, e^{-\beta_n^2 \frac{D_g t}{a^2}}}{\beta_n^2 \left[\beta_n^2 + L(L-1)\right]} \qquad (2)$$

Where β_n's are the roots of

$$\beta_n \cot \beta_n + L - 1 = 0 \qquad (2a)$$

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and

$$L = \frac{a\,RT\,k_L}{HD_g} \qquad (2b)$$

This solution is presented graphically in figure 2, a plot of f versus $\sqrt{\frac{D_g t}{a^2}}$ with L as parameter. We may note that for L greater than about 30 the gas phase resistance controls and for L less than about 0.3 the liquid phase resistance controls. It will now be demonstrated that the principal factor which determines the controlling phase (and thereby the efficiency) is the solubility constant, H.

Let us assume that

1. Average bubble radius, a, is 0.2 cm and average velocity of rise, u_B, is 24 cm/sec.
2. Average gas diffusivity, D_g, is 0.1 cm^2/sec and average liquid diffusivity, D_L, is 1.5×10^{-5} cm^2/sec.
3. Temperature, T, is 298°K.
4. Absorption liquid is a dilute aqueous solution. (This is implicit in 1 and 2, above).

Upon making these substitutions we have:

$$L = \frac{1{,}665}{H} \qquad (3)$$

The dependence of efficiency on H is illustrated in figure 3, a plot of f versus H with $\sqrt{\frac{D_g t}{a^2}}$ as parameter. An "average" absorber might have an unaerated liquid height of about 5 cm and a gas contact time of about 0.22 sec. so that $\sqrt{\frac{D_g t}{a^2}} \approx 0.75$. From figure 3 we can see that the efficiency of an "average" absorber for a moderately soluble gas such as CO_2 ($H > 10{,}000$) would be quite low.

Effect of Chemical Reaction

We have seen that where solubility is low the intrinsic efficiency is low because liquid phase resistance controls and liquid diffusivities are much lower than gas diffusivities. It will also be shown later that where solubility is low the equilibrium limit on efficiency becomes severe. Thus there are two good reasons for using a chemically reactive solution to reduce the equilibrium pressure (raise the solubility) of the absorbed gas above the liquid.

Although the reaction products might be non-volatile, there is still no assurance that liquid phase resistance will be negligible. It is necessary that the reacting substance diffuse through the liquid toward the gas-liquid interface and react at a high enough rate to match the rate of diffusion of the pollutant into the liquid. If reactant diffuses to the interface too slowly or if the reaction rate is too low the reaction zone will be displaced a considerable distance into the liquid with the result that the interface is depleted of reactant and no benefit is obtained.

The situation of greatest interest is that where a very rapid second order reaction yields a non-volatile product. For the approximation that the diffusivities of pollutant and reactant are equal we may use the solution given by Sherwood and Pigford (6):

$$k_L = \left(1 + \frac{q}{C_{Ai}}\right) \sqrt{\frac{2D_L u_B}{\pi a}} \qquad (4)$$

Where C_{Ai} is the concentration of the pollutant in the liquid at the interface and q is the concentration of reactant in the bulk of the liquid.

It can be seen that if the ratio $\left(\frac{q}{C_{Ai}}\right)$ is low, equation 4 becomes identical with equation 1 for physical absorption. In view of the assumptions made in deriving equation 4, it can only be considered to give an approximate indication of the effect of reactant concentration relative to pollutant concentration. For practical use, however, it is quite adequate for setting the order of magnitude of the minimum reactant concentration required to reduce liquid phase resistance. The criterion to use is whether L, as evaluated by equation 2b, is high enough for satisfactory efficiency.

EQUILIBRIUM LIMIT

Up to this point we have been concerned with factors determining the fractional approach to equilibrium. Where a chemically reactive solution yields a non-volatile product this is all we need. For the case of physical absorption, however, the efficiency limit imposed by equilibrium considerations is most important.

If the effect of increasing liquid phase concentration of pollutant is taken into account, the average overall efficiency from time = o to time = t_a is given by:

$$F_a = \frac{V_L RT}{HGt_a}\left[1 - e^{-f\left(\frac{HGt_a}{V_L RT}\right)}\right] \qquad (5)$$

For any particular system and temperature the only variable is the ratio of gas sample volume to liquid volume ($\frac{Gt_a}{V_L}$); which, for convenience will be called "r_s". The effect of the equilibrium limit is shown in figure 4, a plot of F_a versus ($\frac{Hr_s}{RT}$) with r_s as parameter. Values of "f" were taken from figure 3 for $\sqrt{\frac{D_g t}{a^2}}$ = 0.75 and "T" was taken as 293°K. For common situations where r_s might be 100 or more the efficiency is determined almost entirely by the equilibrium limit which can be computed by means of equation 5 with f = 1.0.

We may note from figure 4 that for an "average" absorption system the overall efficiency will be only slightly affected by the intrinsic efficiency. This is shown more clearly by figure 5, a plot of F_a versus H with r_s as the parameter and for the same "average" conditions as figure 4. The gas to liquid ratio, r_s, must be extremely low before the overall efficiency approaches the intrinsic efficiency shown by the line for f = F_a.

DISCUSSION

The methods which have been presented are sufficient for estimating collection efficiencies for most practical purposes. Results of essentially the same methods for treating physical absorption and absorption with chemical

reaction have been compared with experimental data by the authors in a previous paper (ref. 7). Experimental confirmation of the treatment of the equilibrium limited case was presented by Gage (ref. 8). We may conclude from these that while the actual physical situation is more complex than was assumed in deriving the equations, the accuracy of prediction remains adequate for most practical situations.

Where very precise knowledge of absorption efficiency is required it is necessary to determine it experimentally. Also, there are some systems such as ammonia absorption in water where effects such as interfacial resistance or unforseen liquid phase reactions may be significant although not accounted for unless specific information is available. The authors have demonstrated (7) that the results of Roberts and McKee (9) for ammonia absorption by water in several types of small absorbers can be reconciled with results obtained in large industrial absorbers. Such phenomena as internal circulation in the bubbles or concurrent flow of the liquid may also have considerable effect on efficiency. In general, however, one will have either an equilibrium limited case, which is fairly insensitive to intrinsic efficiency, or a chemical reaction case, which can be made very efficient by using proper concentration and a commonly good absorber.

Procedure

Predictions of efficiency for systems operating at room temperature and atmospheric pressure and with a dilute aqueous liquid can be estimated by means of figures 3 and 4 for physical absorption. For more accurate predictions or for unusual conditions of temperature, pressure, or liquid viscosity, figures 1a and 2 and equations 1, 2b, and 5 must be used. Data on diffusivities and other physical properties may be found in sources such as the International Critical Tables, Chemistry Handbooks, and "The Properties of Gases and Liquids" by Reid and Sherwood. Methods for predicting diffusivities and other properties where data are not available or where data must be extrapolated are presented by Reid and Sherwood.

For cases of chemical reaction other than the second order, infinitely rapid, irreversible type, one may consult Dankwerts (ref. 10), van Krevelen and Hoftijzzer (ref. 11) and Sherwood and Pigford (ref. 6) for suitable definitions of k_L. Where the second order, rapid, irreversible type applies the conservative approach is to evaluate C_{Ai} as that concentration which is in equilibrium with the inlet gas. The ratio (q/C_{Ai}) should be in terms of equivalents. That is, the ratio in molar concentrations should be multiplied by the ratio of moles of pollutant combining with a mole of reactant.

The most reliable predictions are those for the equilibrium limited case (r_s greater than about 100). For other cases the efficiency must be checked experimentally.

Definitions of Symbols

A = Designation of transferring component

a = Bubble radiu (cm)

C_a = Average concentration of A in liquid at any instant (mol/cm^3)

C_{Ai} = Concentration of A in the liquid interface (mol/cm^3)

D_g = Gas-phase diffusivity (cm^2/sec)

D_L = Liquid-phase diffusivity (cm^2/sec)

F_A = Overall average collection efficiency

f = Fractional instantaneous approach to equilibrium = $\frac{p_1 - p_2}{p_1 - HC_a}$ = equilibrium collection efficiency

G = Gas flow rate (cm^3/sec)

H = Henry's Law Contant ($\frac{atm}{mol/cm^3}$)

h_1 = Liquid depth before aeration

k_L = Liquid phase mass transfer coefficient ($mols/cm^2\text{-}sec\text{-}mol/cm^3$) based on driving force - $(C_{Ai} - C_a)$

L = Parameter, see equation 2b.

p_1 = Partial pressure of A in inlet gas (atm)

p_2 = Partial pressure of A in outlet gas (atm)

p_e = Partial pressure of A in equilibrium with liquid concentration, C_a (atm)

q = Concentration (average) of B in liquid for one mole of B reacting with one mole of A (mol/cm^3)

R = Gas law constant = 82.057 ($\frac{atm - cm^3}{mol - {}^oK}$)

r_s = Ratio of total gas volume sampled to liquid volume

Definitions of Symbols

T = Absolute temperature (^{o}K)

t_g = Residence time of a gas bubble (sec)

u_B = Bubble velocity relative to liquid (cm/sec)

u_g = Superficial gas velocity ($cm^3/min\text{-}cm^2$)

V_L = Volume of liquid in absorber (cm^3)

π = 3.1416

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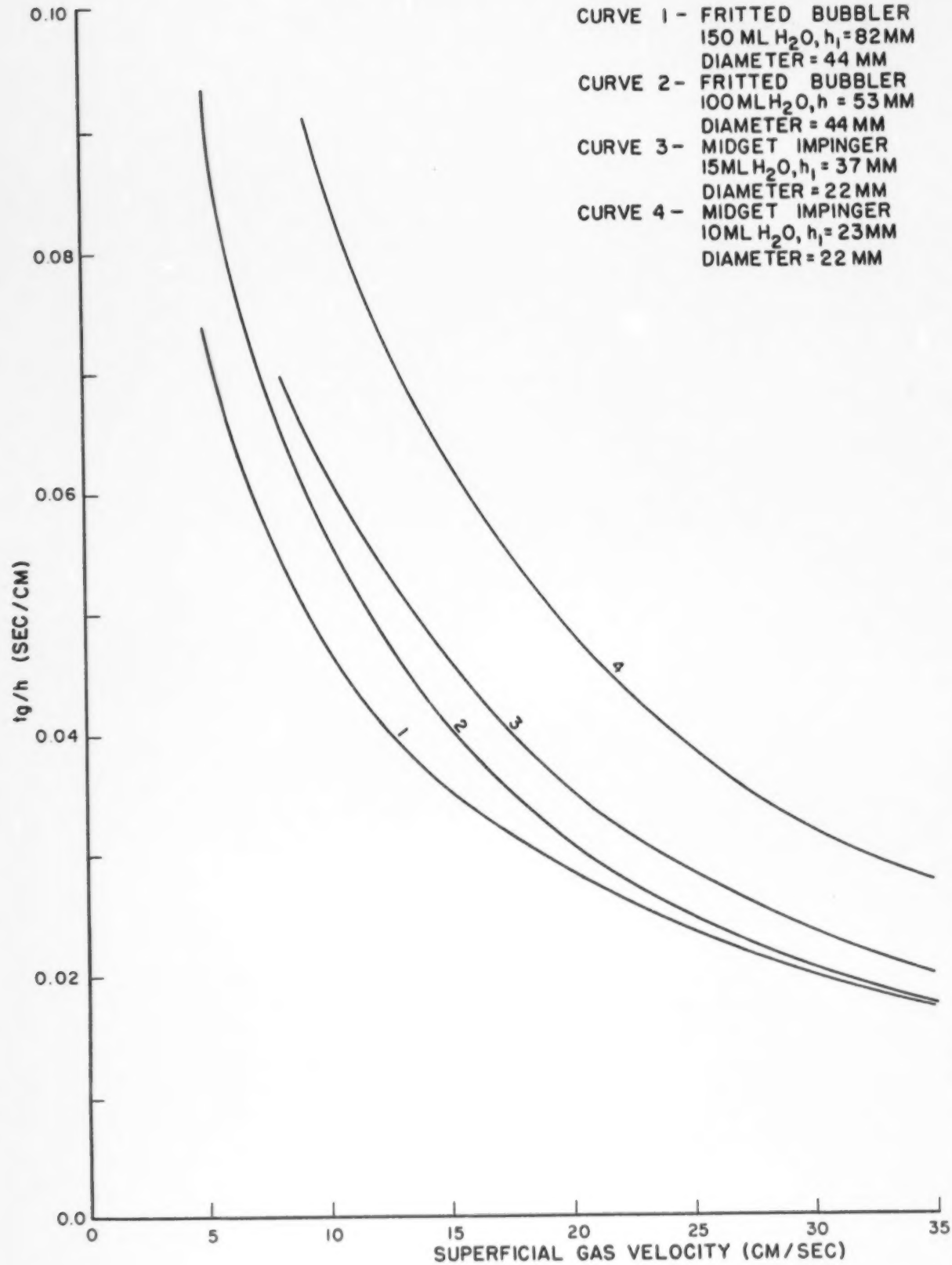
CURVE 1 - FRITTED BUBBLER
150 ML H_2O, h_1 = 82 MM
DIAMETER = 44 MM
CURVE 2 - FRITTED BUBBLER
100 ML H_2O, h = 53 MM
DIAMETER = 44 MM
CURVE 3 - MIDGET IMPINGER
15 ML H_2O, h_1 = 37 MM
DIAMETER = 22 MM
CURVE 4 - MIDGET IMPINGER
10 ML H_2O, h_1 = 23 MM
DIAMETER = 22 MM
tg/h (SEC/CM)
0.10
0.08
0.06
0.04
0.02
0.0
0
5
10
15
20
25
30
35
SUPERFICIAL GAS VELOCITY (CM/SEC)
1
2
3
4

FIGURE 1-G

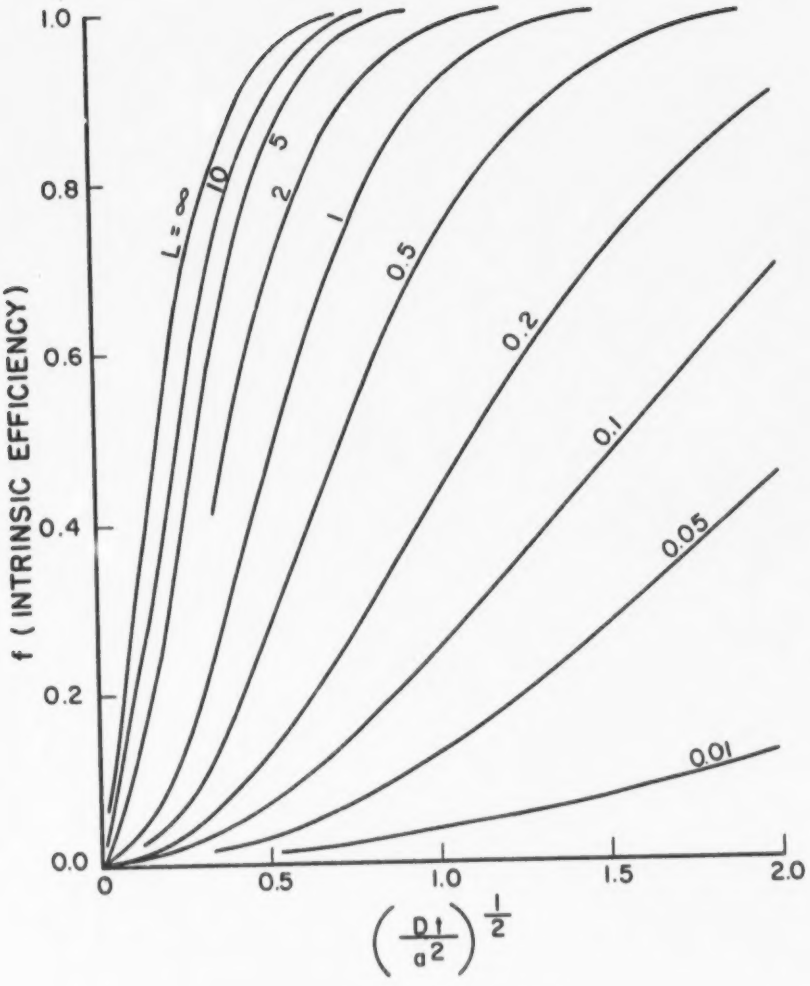
1.0
0.8
0.6
0.4
0.2
0.0
f (INTRINSIC EFFICIENCY)
L = ∞
10
5
2
1
0.5
0.2
0.1
0.05
0.01
0
0.5
1.0
1.5
2.0
$\left(\frac{D\,t}{a^2}\right)^{\frac{1}{2}}$

FIGURE 2-G

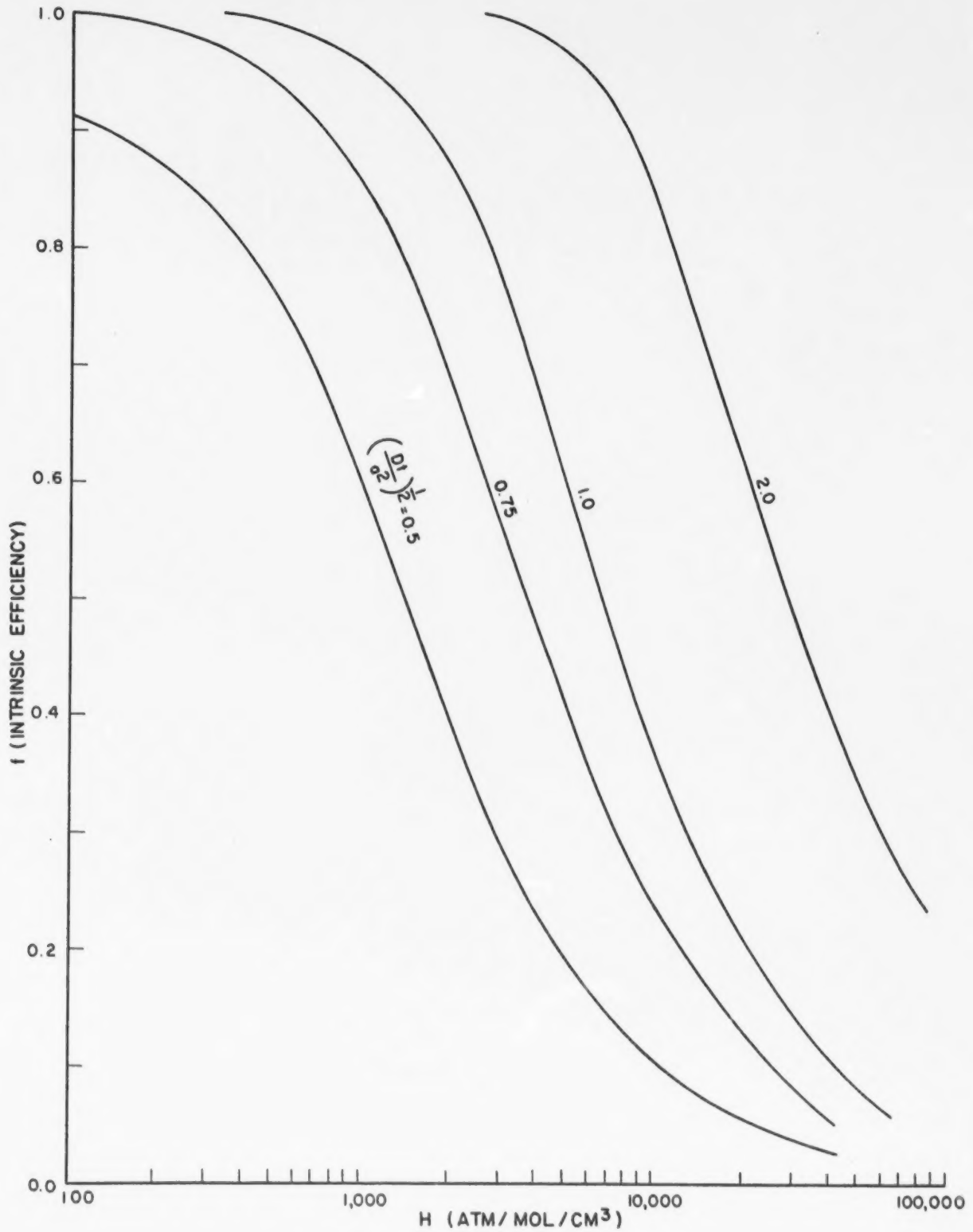
1.0
0.8
0.6
0.4
0.2
0.0
f (INTRINSIC EFFICIENCY)
100
1,000
10,000
100,000
H (ATM/MOL/CM3)
(D1/D2)1/2=0.5
0.75
1.0
2.0

FIGURE 3-G

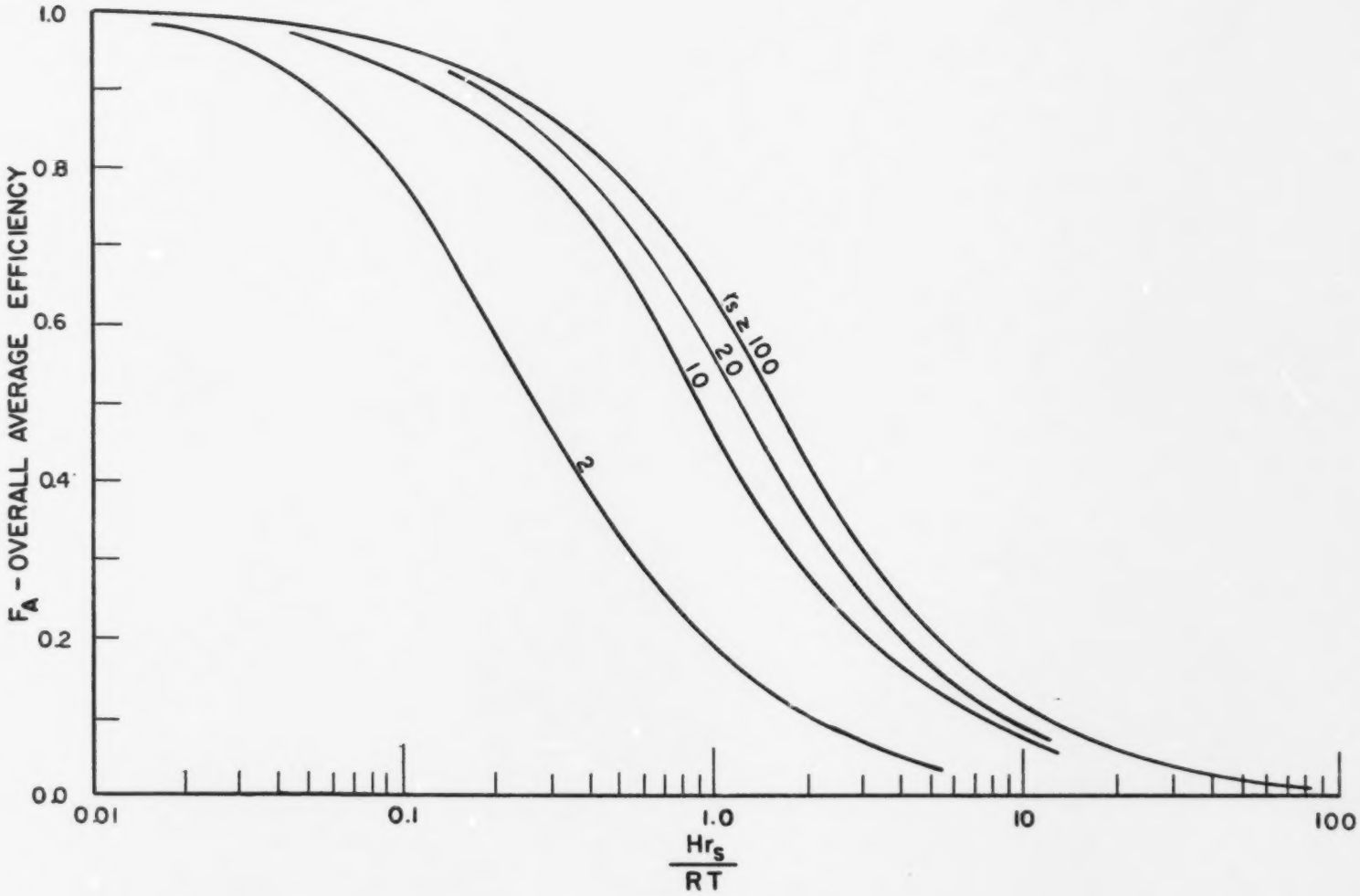
1.0
0.8
0.6
0.4
0.2
0.0
F_A - OVERALL AVERAGE EFFICIENCY
0.01
0.1
1.0
10
100
$\frac{Hr_s}{RT}$
$t_s \geq 100$
2.0
1.0
2

FIGURE 4-G

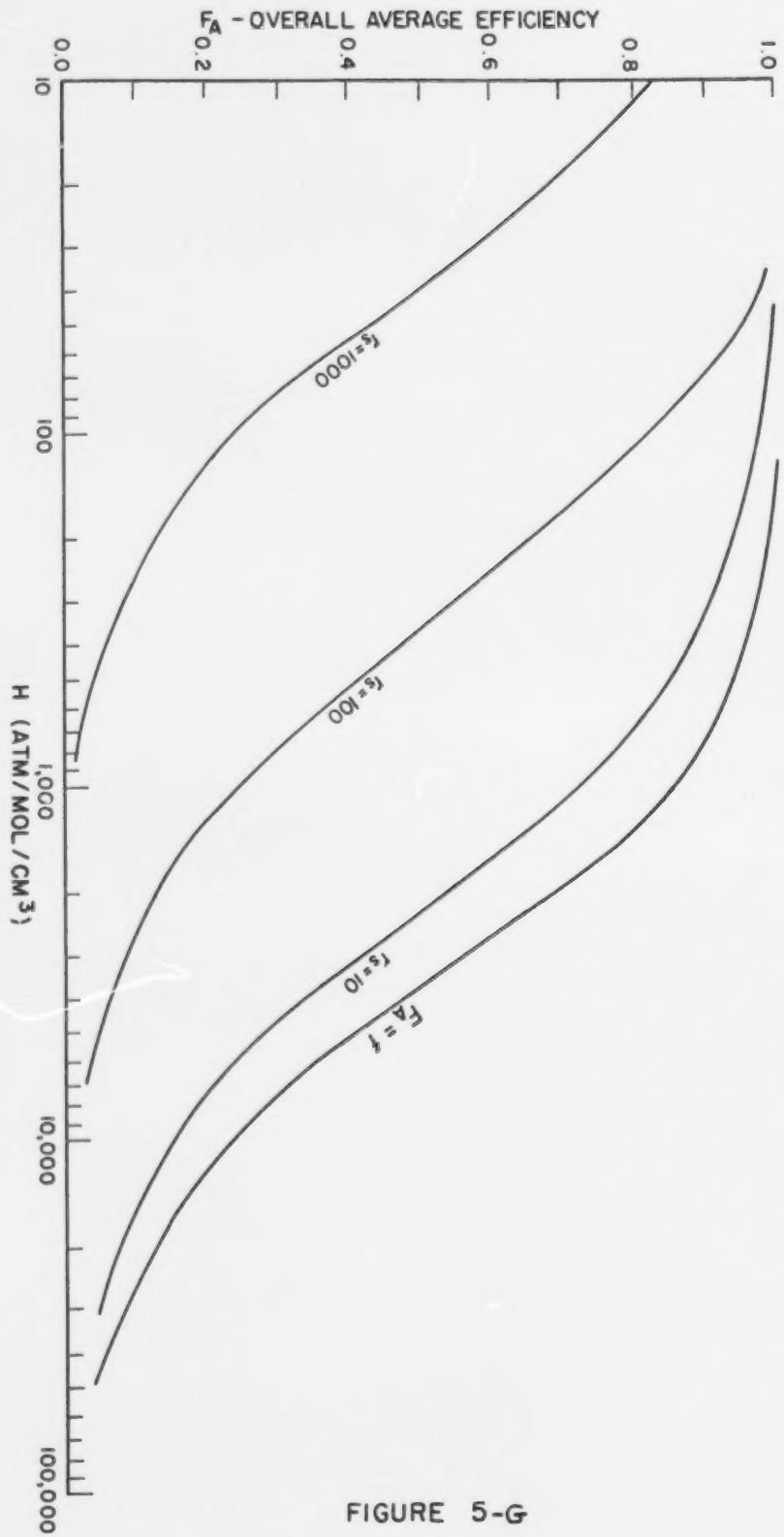
F_A - OVERALL AVERAGE EFFICIENCY
0.0
0.2
0.4
0.6
0.8
1.0
10
100
1,000
10,000
100,000
H (ATM/MOL/CM^3)
f_S=1000
f_S=100
f_S=10
F_A = f

FIGURE 5-G

APPENDIX H

Interim Progress Report on

MASS TRANSFER AND PARTICULATE COLLECTION IN SUPPORTED FROTHS

Walter Workman

Part I. SPIRAL ABSORBER

The purpose of this part of the research work is to characterize the behavior of liquid and gas flow patterns as related to co-current flow and to describe this behavior in its relationship to performance and efficiency of the absorber.

In previous work (1) it was noticed that in bubbling gas through liquids there was an effect of co-current liquid movement. Co-current flow of this type tends to lower the overall efficiency of the absorber because the liquid in contact with the gas is becoming more saturated with the absorbing substance.

Other evidence for co-current flow has been observed by Canadian workers (2). These authors suggested evidence for such flow in bubbling systems where the bubble rate was greater than 3/second. Evidence for this was increased rate of bubble rise. They drew this conclusion from the fact that as the distance the bubbles rose increased (i.e., the bubbling depth increased), the velocity increased, indicating that the continuous phase was moving upward in the path of the bubble. They made no attempt to correlate anything with co-current flow.

It was anticipated that supported (by solid channels) froth systems would be even more susceptible to co-current flow than the unsupported systems cited. The study of a spiral absorber will provide basic information not only on supported froths, but also on a type of apparatus which is itself of interest because of its common use in laboratories.

Equipment Description

A Fisher-Milligan Spiral Absorber is used in the experiments. Figure 1 is a drawing of the absorber as modified for this study. Several modifications of the original equipment had to be made in order to obtain the required data. A conductivity cell was installed to obtain bulk liquid concentration. A conductivity cell was also installed at the top of the spiral path in hopes of obtaining liquid concentration at that point. This proved inadequate because of mixing with bubbles and bulk liquid. The final procedure was to take samples with a hypodermic syringe equipped with a 20 gauge needle, and analyze them in a separate conductivity cell.

A second major modification was the addition of necessary connections to allow for a liquid flow through the absorber. Initial runs were made with the absorber run as a batch absorber but it was

not possible to get the required data because the non-steady state operation required sampling time and sampling procedures beyond the capabilities of the setup. The constant liquid flow through the absorber allowed the system to come to a steady state in which repeated measurements could be made without regard to the time element encountered before.

Experimental Procedure

The basic procedure was to obtain steady state values, for numerous parameters named later, at a particular setting of liquid and gas flow rates. The flow rate of each was varied separately with appropriate data taken in each case.

The data needed were of two kinds:

1. Absorption data which included gas and liquid concentration at the entrance and exit of the spirals, the temperature and the pressure of the system.

2. Data on the residence time of the gas and liquid in the spirals. This data was obtained by the use of photographic techniques which will now be described.

It was impossible to trace the movement of any one bubble throughout the entire equipment unless the bubbles came from the nozzle at a very slow rate, say 1 bubble per 3 or 4 seconds. This kind of data is useless because the bubbling rate is much lower than would ever be encountered. Such data cannot be extrapolated to the required conditions because the residence time for any one bubble depends greatly on the bubbling rate and amount of co-current flow, which is exactly what is to be determined. To overcome this difficulty a movie camera, running at 64 fps, was set up to take pictures of the absorber in operation. An electric timer was photographed along side the bubbler. Two lines were ruled vertically 1 inch apart on the absorber from which a scale factor could be obtained. By using a single frame projector it was possible to measure bubble diameters and the time necessary for a bubble to advance one inch.

To measure the liquid flow rate, ink was introduced at the bottom of the spiral. Again the timer was photographed along side the absorber and the time necessary for the ink to reach the top was determined from the pictures.

Correlation of the Data

Figure 2 is a plot of the equilibrium relationship for the system CO_2 - air - water. Included also is an operating line for one run. It is noted that the direction of the slope of the operating line shows the characteristics of a co-current system. More important is the actual slope of this line. It has a slope of about 300. Since the plot is in terms of mol fractions, this slope represents an experimental L/G of 300 mols liquid/mol gas. This represents a tremendously effective liquid flow relative to the gas.

The photographic data is sufficient to calculate effective liquid and gas flow rates. Using this data, a value for the ratio of gas volume associated with the liquid volume can be calculated. In the particular run in question the ratio is quite small, 0.185. A look at Figure 5 from Appendix G (ref. 5) shows F = f, i.e., the average efficiency at time t equals the intrinsic efficiency. This shows that it is not equilibrium limited.

From the photographic data the bubbles were determined to have an average radius, a, of 0.55 cm, and the time of rise was determined as 2.4 seconds. The value of $\left(\frac{Dt}{a^2}\right)^{1/2} = 0.86$. Calculation of a value of L (the parameter on Figure 2, Appendix G) indicates L=0.063 (showing it to be liquid phase controlled).

Using the calculated value of $\left(\frac{Dt}{a^2}\right)^{1/2}$ and L the efficiency can be read from Figure 2, Appendix G, as 17%, the experimental efficiency was 15.2%.

The agreement here is good. Although co-current flow figured in liquid flow rate, gas residence time, L/G, and the amount of liquid associated with the gas, it apparently did not cause the system to approach the equilibrium limit with respect to efficiency. All the data will have to be evaluated before any such general statement can be made, however.

Part II. MASS TRANSFER AND PARTICLE COLLECTION IN FOAMS

Purpose of the Work

The general objective of the work is to study mass transfer and particle collection in supported foams. This broad generalization must be broken down into specific areas to state the real goals of the work.

It has been demonstrated that column diameter, the type of packing, and packing spacing has an effect on foam height. One phase of this work is to determine just what this dependence is. In this connection emphasis will be placed on a particular kind of packing. The construction of this packing call "Egg Crate Packing" is discussed in the section on equipment design. The reason for the choice of this packing is that it serves to support the foam making a substantial increase in the foam height and thereby an increased surface area per unit volume of liquid. The result is a lower density for the portion of the column containing liquid and a lower pressure drop due to head of liquid.

The diffusion mechanism for both mass transfer and particle collection will be studied. For this reason a substantial foam height is desired.

It has been shown (6, 7, 8) that properties of both liquid and gas have effects on the efficiency. If the gas stream considered contains particles the physical properties of the particles will

affect the performance. These effects will be considered as they relate to foaming and the properties of the foam in their connection with efficiency.

Equipment

The basic column is built of aluminum and glass. It consists of a framework of aluminum angle and 1/8" aluminum sheet. 4" x 12" glass windows are glued in place with Pliobond. The basic column is 4" x 4" x 36". The sieve plate is located 12" from the bottom, and a 4" x 4" x 30" entrainment section is attached to the top.

The support for the foam is made of 1/8" Lucite machined to make an "egg crate" packing when assembled. The packing can be either run in separate sections or in several sections either butted together or separated. The sections are 4" and 6" in length with openings when assembled of 1/2", 3/4", and 1". Separation of sections of packing have previously been done by aluminum strips bent in the shape of a "V". This type of separator will be abandoned because of its tendency to promote channeling. In future work a thin strip of aluminum running around the inside periphery of the column will separate the sections.

The sieve plate is not equipped with downcomers. This may eventually be done. This factor will have a large effect on the allowable open area on the tray. Without downcomers the open area will be greater than about 15% to allow for liquid weeping through the holes.

The sieve plate itself is made of 0.035" aluminum sheet. The plate is easily removable and various designs as to hole size, spacing, arrangements, and percent open space are readily interchangeable. The plate for which the data given in this report was taken has 1/16" holes drilled on 1/4" diagonal centers. The plate has an open area of 18.5%.

Previous Work in General

Most of the work on particle collection in foams seem to be reported in the Russian literature. For the most part the equipment has been rather large and built with downcomers. The Russian work has been with large particles (15 to 25 microns).

The Russian workers also report many correlations as to foam height, efficiency for particle collection, and correlations of physical parameters of the system as they relate to performance. Other workers have studied the physical characteristics of foams, their forming, and their stability. There are also many references to the general subject of mass transfer and efficiency of mass transfer in foams.

With all this background in the literature, little seems to be reported in the specific areas pertinent to the intended work. As mentioned before the work on particles has been with large particles where an inertia rather than a diffusional mechanism was the

predominant factor. The later Russian workers have discounted the effect of column diameter on foam height, although earlier workers seem to have observed such a phenomenon (8).

Proposed Work

Future work can be classified into three fields--properties of foam systems as such, mass transfer, and particle collection in foams.

Under foam systems there are three areas to study--foam height, pressure drop and flooding. Some of the literature is helpful here, but even better is the experimental data that has been obtained from the apparatus.

Mukhlenov (8) presents several correlations for his work with foam on sieve trays. He presents correlations for foam height which are a function only of superficial gas velocity and the original height of liquid on the tray. The apparatus used was 36 and 86 mm in diameter. In the particular setup used there was no overflow orifice and no weeping of liquid through the tray. Under these conditions he concluded that foam height did not depend on the diameter and geometry of the apparatus. His correlation fit his data very well, but he noted that they were good only in the absence of weeping. At present no such correlations have been found that deal with dual flow trays.

Mukhlenov also studied foam systems with overflow orifices. Again he was able to present correlations for foam height which depended primarily on gas velocity, original height of liquid and some dimension relating height and width of the overflow orifice. His work was still restricted to trays with no weeping.

Experimental Data on Supported Foam

Figure 3, based on our data, shows that foam height definitely depends on the packing height used. It is noticed that the foam height exceeded the packing height in every case. Figure 5 shows that foam height depends on the diameter of the apparatus (i.e., packing size).

It was noted that spacing of the packing sections had a big influence on foam height and stability of the foam generated. With the sections of packing touching the plate there seemed to be a tendency to channel and bubbling was uneven on the tray. This was generally true no matter what bubbling rate was considered. With the packing separated from the tray a more even bubbling rate was observed across the entire tray, the foam was evenly distributed up through the packing, the foam was higher, and the operation was more stable with less channeling. Equally important was the fact that the foam was less dense, giving a lower pressure drop.

It was also noted that when more than one section of packing was used, it was better to separate the sections allowing the foam to redistribute itself between the sections. In this connection

some attempt was made at determining an optimum distance of separation. It was found that if the distance was greater than about 1" the foam was not supported and the height fell. If the spacing was less than about 1/4" channeling similar to that with no separation occurred. It appeared that about 1/2" separation was best.

In part of the work separation was accomplished by friction between the walls of the column and the packing, but this procedure was not suitable for all packing because of differences in machined widths. It was decided to use aluminum strips of various widths bent into "V" shapes as the separators. This did not work. The strips prevented redistribution of foam across the tray with channeling and dead zones appeared. In future work strips of aluminum running around the entire inside periphery of the column will be used as separators.

Other Factors

The design of the sieve plate itself may have an effect on the foam height and stability. Russian workers (8, 9) have reported that over a wide range of hole size and bubbling rates the velocity in the openings have no effect, but the superficial gas velocity in the open column is important. The conclusions were drawn from trays without weeping. Since weeping affected height under certain conditions there is reason to suspect that the height of foam will depend on hole size if the latter has any effect on the amount of weeping. It is a point that will be investigated.

Liquid properties have an effect on formation and stability of foams (9). The two properties most influential are viscosity and surface tension. Viscosity effects can be studied by varying temperature, by the use of additives, and by the use of different liquids. More work, however, has been done on surface tension. Addition of surface active agents results in a marked rise in the thickness of foams. The effect of surface tension may also be studied by using different liquids.

DeVries (11) has studied the structure and stability of foams. His work was done with stationary and not dynamic foams. He presents evidence that the stability of foams can be traced to the effect of liquid drainage and gas transfer from the foam. Surface tension plays a major role in his stability determination. He reasons that the consideration of surface tension alone however would lead to a more stable foam for the greater surface tension because of the increased resistance to rupture of the film. It is his belief that surface active agents increase the stability because they form a monolayer on the surface of the bubble which, by electrostatic repulsion, serves to prevent drainage. The problem with trying to correlate this work with the dynamic system is that no account has been made for collision of bubbles and this effect on film rupture.

Pozin and Tumarkina (12) have studied the effects of viscosity and surface tension of dynamic foams. These properties were varied separately to distinguish between the effects. They arrived

at no correlations but in general it was found that increases in surface tension and viscosity decreased the height of the foam. Much of their original data is given in the paper. Their work was done by varying the liquids used. No surface active agents were added.

No attempt apparently was made to correlate pressure drop and flooding in the mentioned equipment (8), however Mukhlenov along with Pozin et. al. (9) considered pressure drop in a limited manner. About the only conclusion published was that the pressure drop definitely was lower than that observed in a bubbling system. Figure 4 is a plot of pressure drop versus gas velocity for the supported foam apparatus.

A factor which these workers have considered very little has been flooding and especially as liquid carry over in the exit gas stream. Under the bubbling conditions encountered (up to a superficial gas velocity of 15 ft/sec), it is difficult to believe that no entrainment was encountered. This type of flooding has presented a problem in most of our experiments performed so far. Drops of water were carried out of the column as entrainment at gas rates greater than about 20 - 25 cfm, (about 3 ft/sec). The Figures (3, 4, 5) show the limits of the range of gas velocities that could successfully be run. For convenience, Figure 1 is a plot of flow rate vs. superficial gas velocity.

There seem to be two solutions to the entrainment problem. First an extra section of column may be added to serve as an entrainment separator, or second, an entrainment separator of, say, wire mesh may be added. A 4"x 4"x 30"entrainment separator has been built and added to the column under study.

Particle Collection

The foam method is apparently an efficient method of collecting particles (13, 14). Most of the work has been reported by Russian workers. The work for the most part was with large particles (15 to 25 microns), where an inertia mechanism controlled (14). Some mention was made however to the collection of small particles. In general the equipment was less efficient at catching the smaller particles.

The data for the apparatus used indicated that almost complete removal, 98.5%, of large dust particles was achieved in a foam of 60mm height (13). It was also noted that the plate itself was serving to collect a substantial portion of the particles by impingement. Collection efficiency for this type of scrubber could be correlated by applying a Stokes type equation. This means that collection efficiency is linear with gas velocity, a factor they did not note in their publication.

Several correlations for the efficiency of the equipment are given but all deal with an inertia mechanism and most of them have factors specific to the equipment used. It is not felt they are of sufficient importance to present here.

Liquid and dust properties seem to have a large influence on the collection efficiency. Classification seems to be based mostly on a water system as the standard hydrophyllic dusts are better caught than hydrophobic. Surface active agents have a negative effect on the collection efficiency of hydrophyllic dusts whereas they have little or no effect on hydrophobic dusts. This indicates that surface active agents will increase the collection efficiency of the latter because of the increased foaming and no adverse surface effects. Surface active agents will decrease the efficiency for hydrophyllic dusts even though the foaming is greater in some cases (7). It was noted that for hydrophyllic dust the concentration trapped in the liquid has no effect on efficiency because of the high rate of renewal of surfaces between gas and liquid phases.

Mass Transfer

Mass transfer efficiency should be increased in the foam system over that for a bubbling system because of the increased surface area. Preliminary calculations and limited data are available for this.

Because of the parallel work being conducted in spiral absorbers with CO_2, the system CO_2 - air - water was chosen for preliminary runs. Using the best known methods available (1) a prediction of efficiency was made for the equipment. The correlation used was:

$$f'_L = \left(\frac{2\,D}{\pi a\, u_B}\right)^{0.5} \frac{6\,P}{H\,\rho' g}$$

and: $$(1-f_L)^n = (1-f_1)^n$$

The radius of the bubble was taken as about 0.5 cm. The number of bubble diameters traveled (n) was estimated from the experimental data for the foam and was found to be 26 for the runs in question. Various predictions gave efficiencies of 4 to 6%. Experimental values were about 3%. Predictions for two other liquid phase controlled systems, nitrogen and oxygen, were calculated. Because of the relatively low diffusivity the predicted efficiency was ≈0%.

Predictions for gas phase controlled systems were better however. Using the same data for bubble diameter and foam properties as for CO_2, the value of $\left(\frac{Dt}{a^2}\right)^{0.5}$ was calculated as 0.38 for chlorine, corresponding to an efficiency of 85%. For ammonia the value of $\left(\frac{Dt}{a^2}\right)^{0.5}$ is 0.54 and the predicted efficiency is 87%. No experimental work has been done to verify the last prediction, but the necessary materials have been ordered to make the check.

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THE SYSTEMS TO BE STUDIED

1 - Mass Transfer

It is anticipated that most of this work will be done with two systems--CO_2 $^{-H_2O}$ and NH_3 $^{-H_2O}$. CO_2 being chosen as an example of a liquid phase controlled system, NH_3 is considered gas phase controlled.

The gas chromatograph will be used for gas analysis if possible. Suitable column packing has been obtained. Even if this does not work, analysis of the systems should be possible with no insurmountable technical difficulties. The water solution can be readily titrated and the gas sample can be drawn through suitable absorption media then titrated.

2 - Particle Collection

This work will be performed with very small particles (less than 0.1μ). Much of the work very probably will be done in water, although some aspects may have to be examined in other systems.

It is anticipated that the particles will be made by the burning of a metal-organic compound. Several references to this type of work can be found. (15) This method can be made to give small particles that are usually an insoluble oxide of the metal in the metal-organic.

Because of their very small size it will be impossible to dtudy their characteristics with a light microscope; therefore, it will be necessary to use the electron microscope. It will be attempted to use light scattering techniques for the analysis of the gas stream. The ability to use it will depend on several things:

1. The ability to correlate dust properties with readings from the instrument.

2. The ability to make enough smoke to analyze. This would be impossible with a La Mer generator unless a radical design change was to take place.

3. The ability to create a device that is sensitive enough. A modification of the unit now available may work here. The unit now available has glass tubes through which the sample passes. The glass scatters a considerable amount of light giving a constant high background. It is believed that elimination of this tube may help considerably.

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SPIRAL ABSORBER

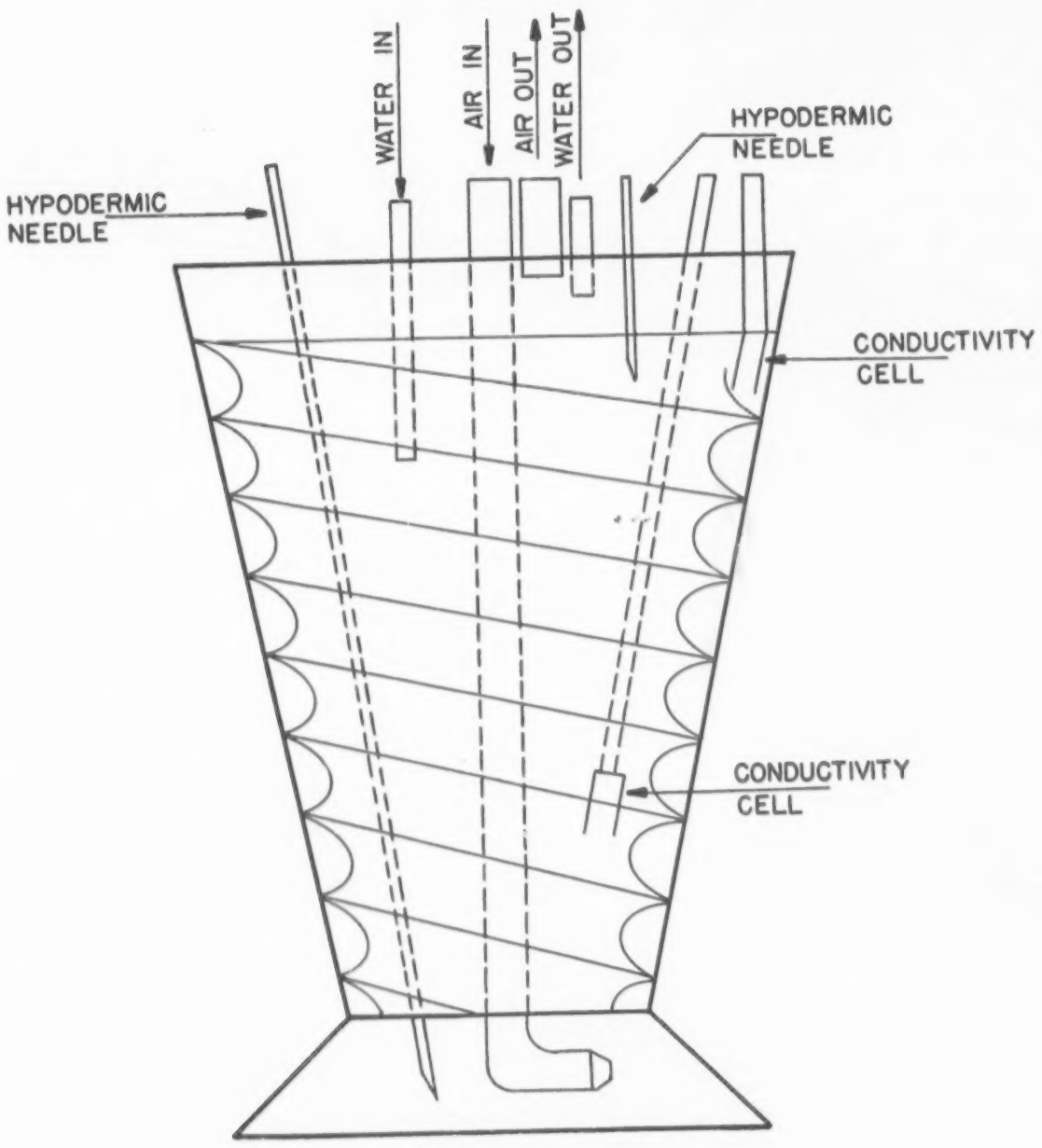

FIGURE 1-H

PLOT OF EQUILIBRIUM DATA FOR CO_2-WATER, ALSO SHOWING OPERATING LINE FOR NO. A-2

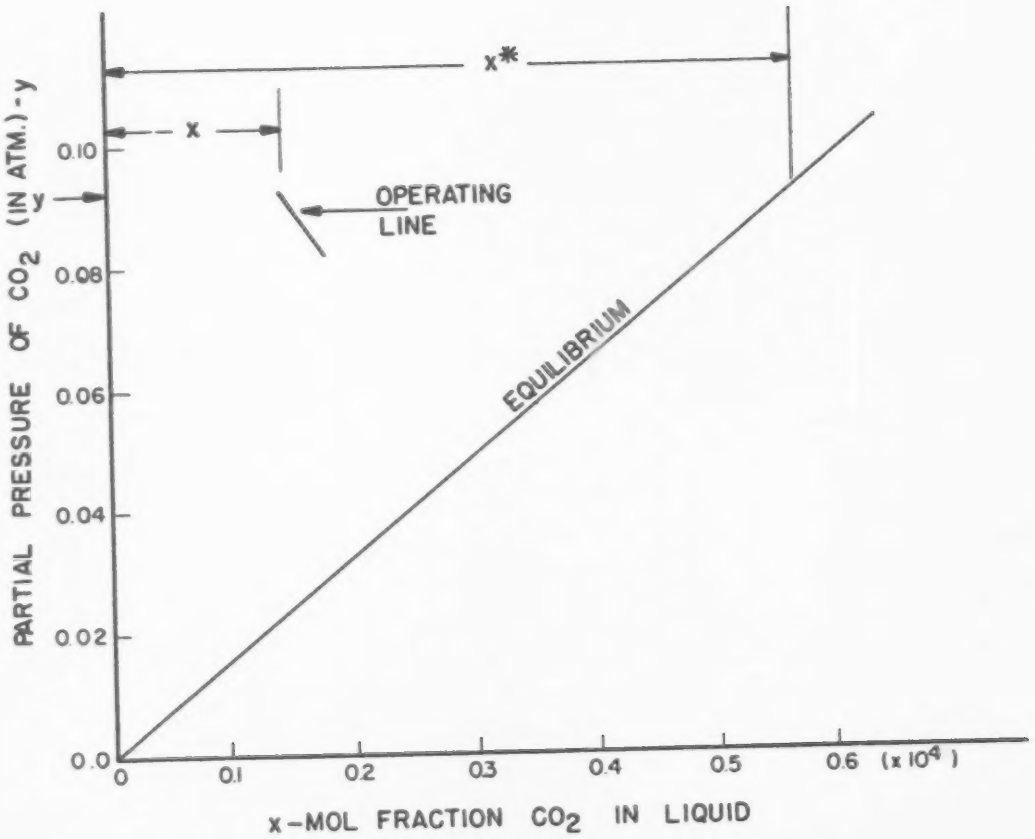

FIGURE 2-H

FOAM HEIGHT vs. SUPERFICIAL GAS VELOCITY

CURVE 1 2 SECTIONS OF 4"x ½"x½" PACKING SEPARATED ½" (FROM TRAY AND EACH OTHER)

CURVE 2 1 SECTION OF 4"x ½"x ½" PACKING SEPARATED FROM TRAY BY ½"

CURVE 3 NO PACKING

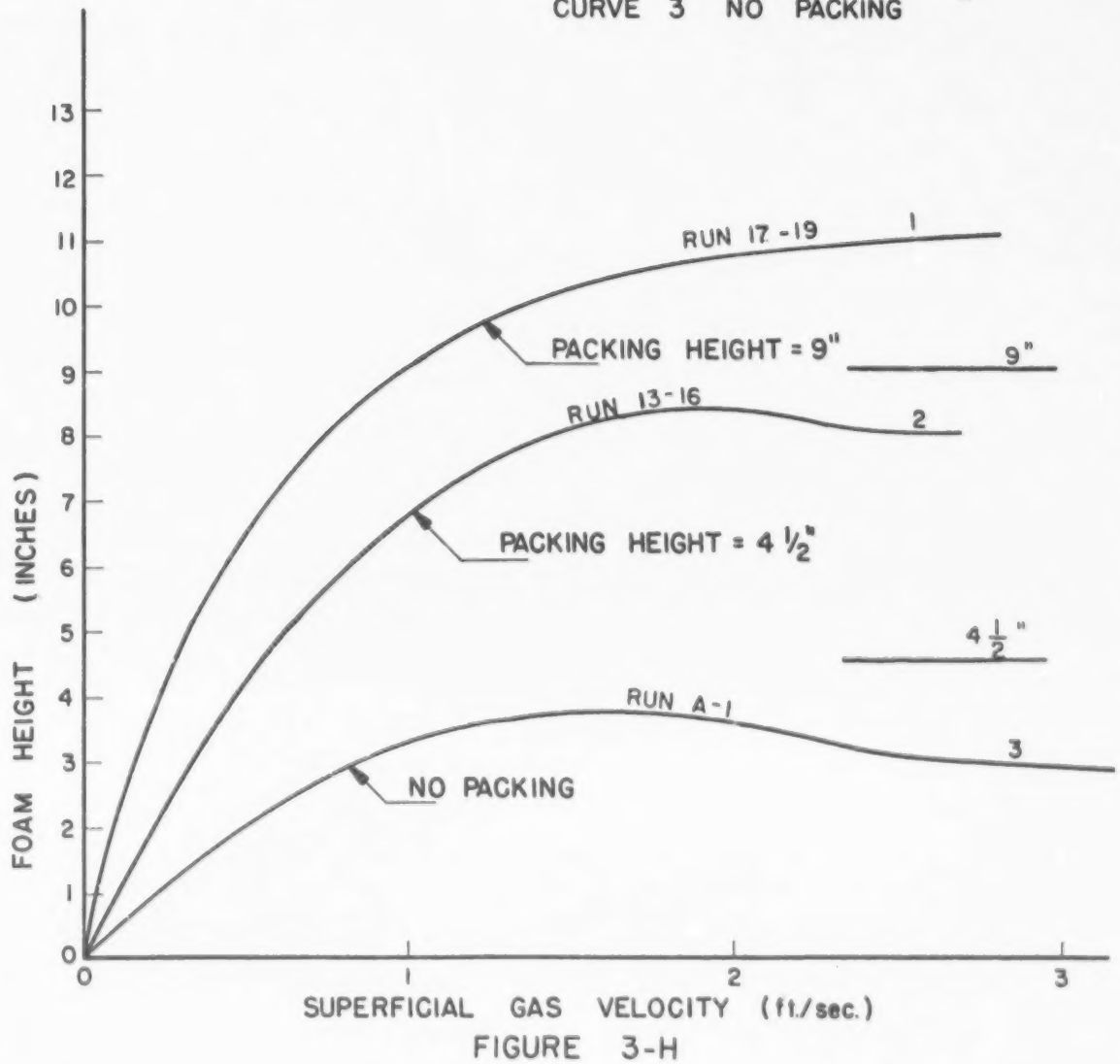

FIGURE 3-H

PRESSURE DROP vs. SUPERFICIAL GAS VELOCITY

CURVE 1 — 2 SECTIONS OF 4" x ½" x ½" PACKING SEPARATED (FROM TRAY AND EACH OTHER) BY ½"

CURVE 2 — 1 SECTION OF 4" x ½" x ½" PACKING SEPARATED FROM TRAY BY ½"

CURVE 3 — NO PACKING

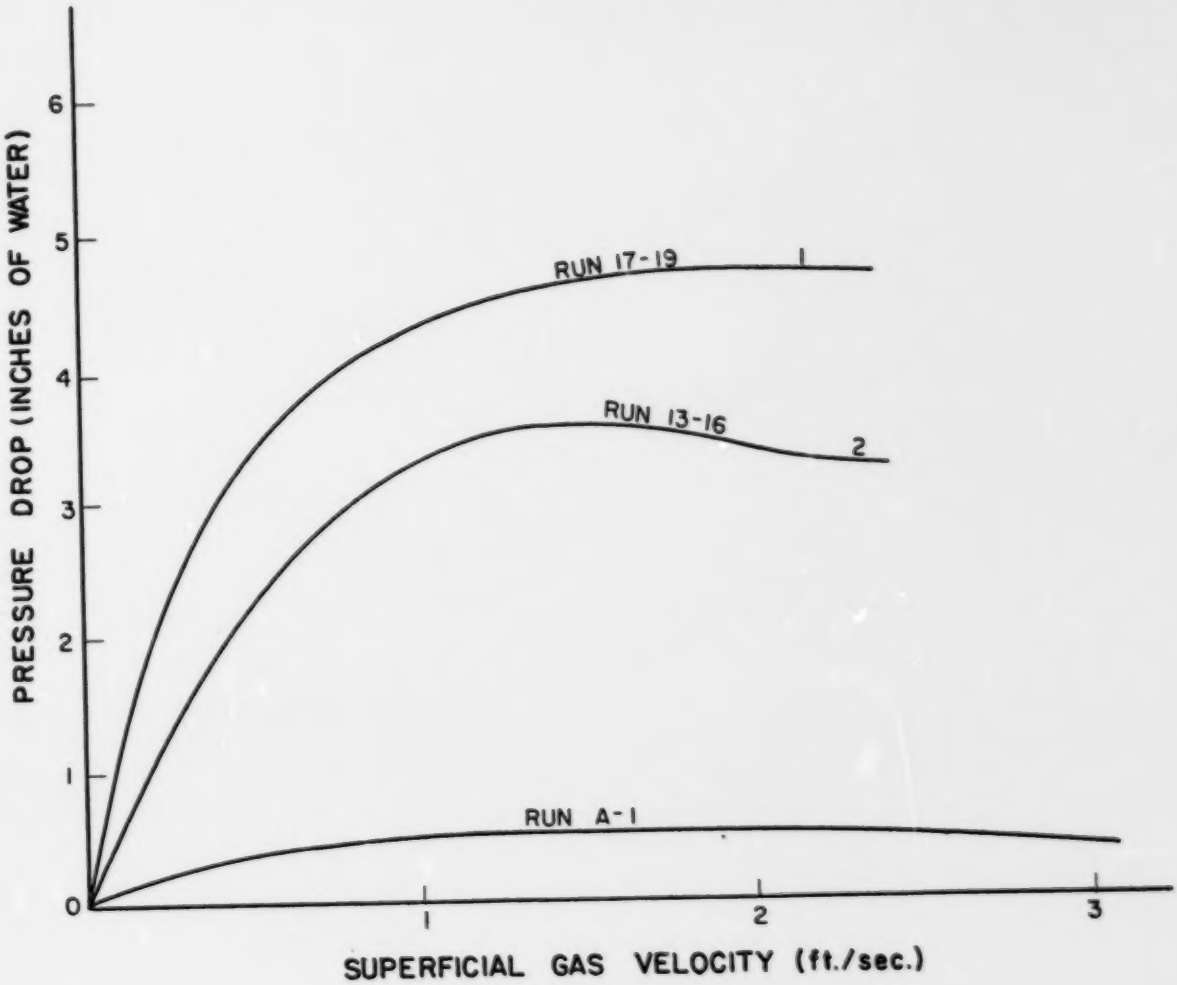

FIGURE 4-H

FOAM HEIGHT vs. SUPERFICIAL GAS VELOCITY

CURVE 1 1 SECTION 6" x ½" x ½"
NO SEPARATION
BETWEEN PACKING
AND TRAY

CURVE 2 1 SECTION 6" x ¾" x ¾"
NO SEPARATION
BETWEEN PACKING
AND TRAY

CURVE 3 NO PACKING

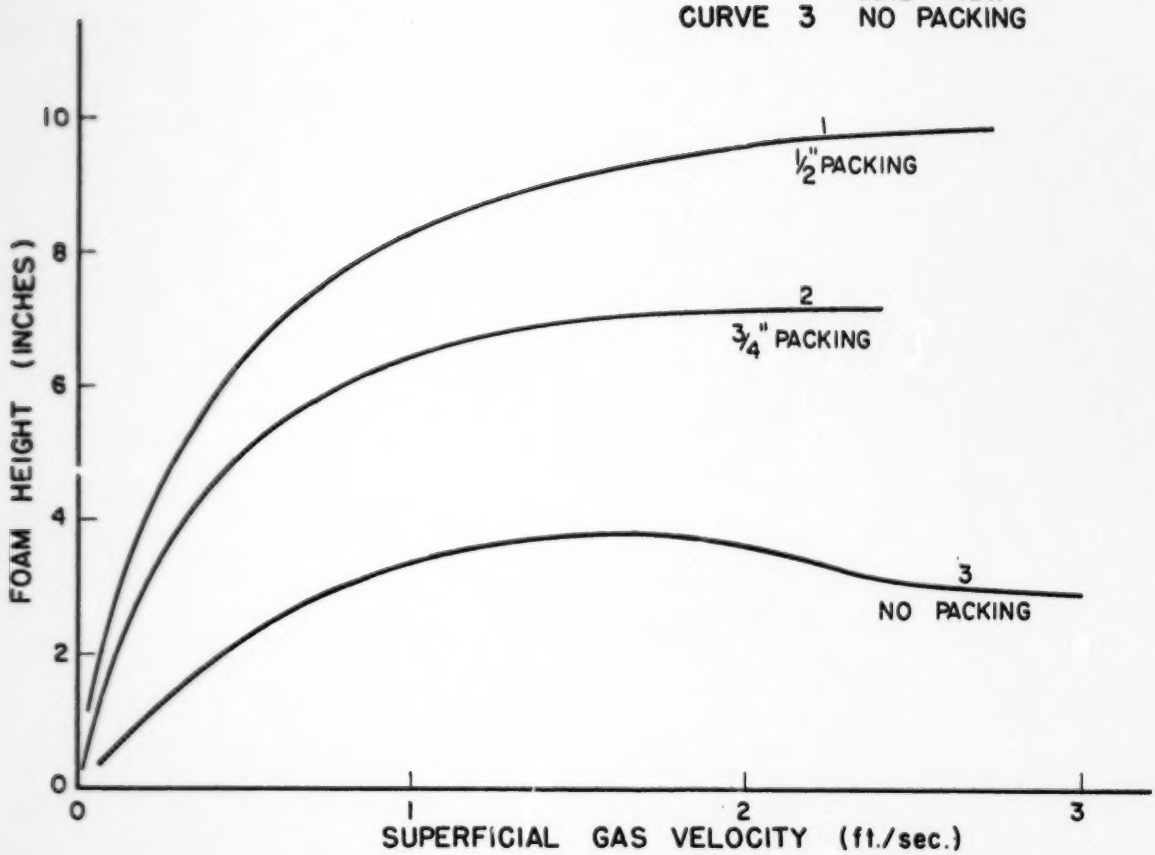

FIGURE 5-H

SKETCH OF EXPERIMENTAL APPARATUS

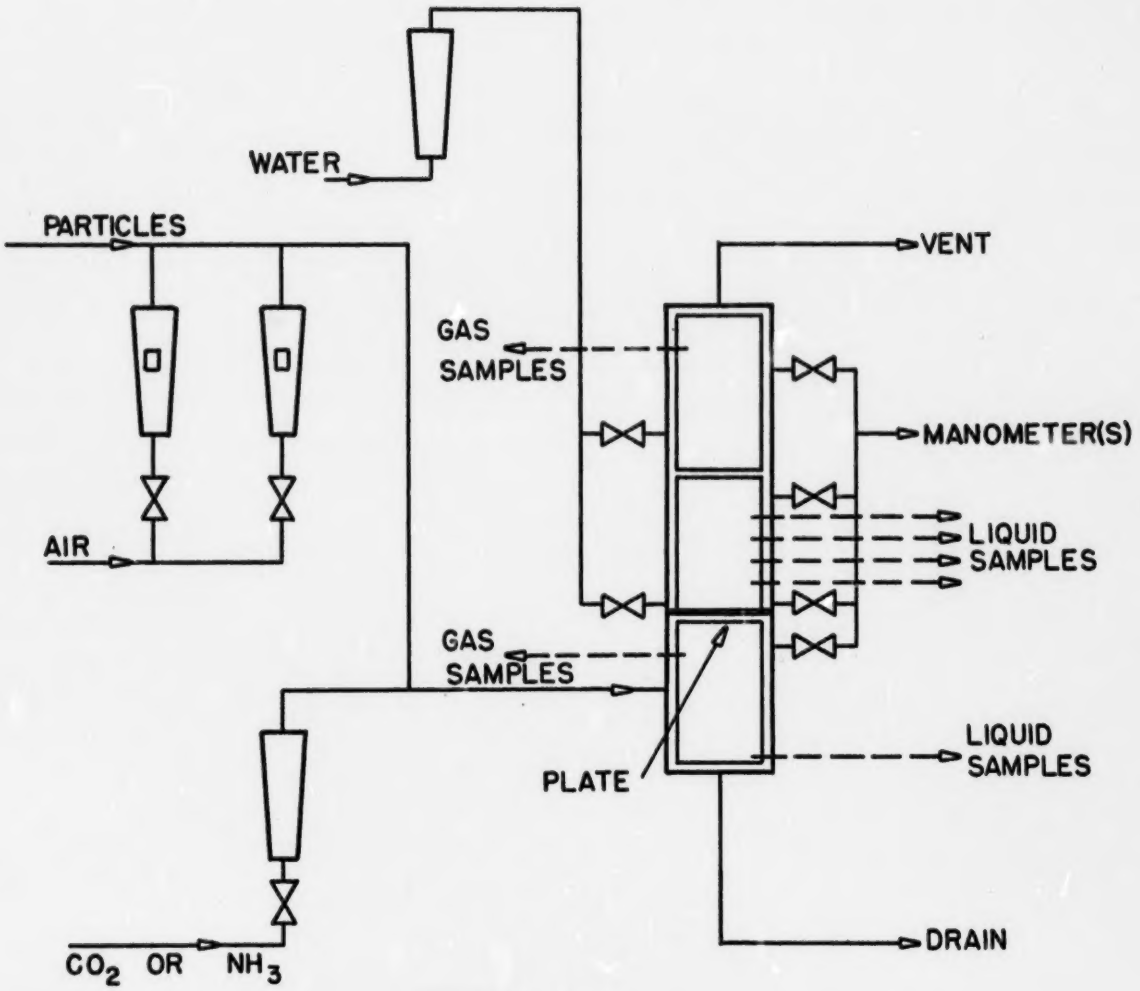

FIGURE 6-H